V.4 HYDRODYNAMIC MODELING

This study focuses on five individual estuarine systems in Chatham, Massachusetts: Stage Harbor, Bassing Harbor, Sulphur Springs, Taylors Pond, and Muddy Creek. Applied Coastal utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in these systems. The particular model employed was the RMA-2V model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. The model is widely accepted and tested for analyses of estuaries or rivers. Applied Coastal staff members have utilized RMA-2V for numerous flushing studies on Cape Cod, including West Falmouth Harbor, Popponesset Bay, Pleasant Bay, Falmouth "finger" Ponds, and Barnstable Harbor.

V.4.1 Model Theory

In its original form, RMA-2V was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by a Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). Graphics generated in support of this report primarily were generated within the SMS modeling package.

RMA-2V is a finite element model designed for simulating one- and two-dimensional depth-averaged hydrodynamic systems. The dependent variables are velocity and water depth, and the equations solved are the depth-averaged Navier Stokes equations. Reynolds assumptions are incorporated as an eddy viscosity effect to represent turbulent energy losses. Other terms in the governing equations permit friction losses (approximated either by a Chezy or Manning formulation), Coriolis effects, and surface wind stresses. All the coefficients associated with these terms may vary from element to element. The model utilizes quadrilaterals and triangles to represent the prototype system. Element boundaries may either be curved or straight.

The time dependence of the governing equations is incorporated within the solution technique needed to solve the set of simultaneous equations. This technique is implicit; therefore, unconditionally stable. Once the equations are solved, corrections to the initial estimate of velocity and water elevation are employed, and the equations are re-solved until the convergence criteria is met.

V.4.2 Model Setup

There are three main steps required to implement RMA-2V:

- Grid generation
- Boundary condition specification
- Calibration

The extent of each finite element grid was generated using contour data developed for the Town's Geographic Information System (GIS), as well as 1994 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of each system based on the tide gauge data collected in Nantucket Sound and Pleasant Bay. Freshwater recharge boundary conditions for Muddy Creek and Frost Fish Creek were specified to approximate average fresh water inputs to the systems. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several (15+) model calibration simulations for each system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.4.2.1 Grid generation

The grid generation process was simplified by the use of the SMS package. The digitized shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary. Information about each grid is provided in Table V-7. Figures V-40 through V-44 illustrate the finite element grids for each system modeled: Stage Harbor, Bassing Harbor, Sulphur Springs, Taylors Pond, and Muddy Creek. With the exception of groundwater inputs entering Muddy Creek and Frost Fish Creek, the embayments were represented by two-dimensional (depth-averaged) elements.

The finite element grid for each system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties of each estuary. Fine resolution was required to simulate the numerous channel constrictions that significantly impact the estuarine hydrodynamics. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary. Reference water depths at each node of the model were interpreted from bathymetry data obtained from a combination of sources, including 1) recent fathometer and/or ADCP surveys in Stage Harbor, Bassing Harbor, and Taylors Pond; 2) recent manual surveys of Muddy Creek, Upper Frost Fish Creek and Cockle Cove Creek; 3) existing NOAA data for Stage Harbor; 4) previous bathymetric survey of Bassing Harbor (ACI, 1997); and previous bathymetric surveys of the Sulphur Springs/Bucks Creek and Taylors Pond Systems (Stearns and Wheler, 1999)

Grid resolution was governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability in each system. Relatively fine grid resolution was employed where complex flow patterns were expected. For example, smaller node spacing in marsh creeks and channels was designed to provide a more detailed analysis in these regions of rapidly varying flow. Also, elements through deep channels (e.g., Stage Harbor Inlet channel) were designed to account for rapid changes in bathymetry caused by inlet shoaling and scour processes. Widely spaced nodes were often employed in areas where flow patterns are not likely to change dramatically, such as Crows Pond, or Sulphur Springs. Appropriate implementation of wider node spacing and larger elements reduced computer run time with no sacrifice of accuracy.

Areas of marsh in the South Coastal Embayments (i.e., Sulphur Springs/Bucks Creek, Cockle Cove Creek, and Taylors Pond/ Mill Creek) were included in the models because these marsh areas are a large portion of the total area of these systems, and have a significant effect on the hydrodynamics of these embayments. In the other modeled systems, marsh areas were not included in order to simplify the modeling effort without impacting model accuracy. This is justified by the fact that the models calibrated and verified well without the inclusion of areas of marsh.

Table V-7. Characteristics of numerical grids developed for hydrodynamic analyses.					
System	Nodes	Elements	Max. Depth (ft, NGVD)	Min. Depth (ft, NGVD)	location of max. depth
Stage Harbor	3973	1466	-18.4	0.0	Stage Harbor Inlet
Bassing Harbor	4419	1443	-18.3	2.3	Crows Pond
Sulphur Springs	7882	2728	-4.5	2.0	Bucks Creek
Taylors Pond	5202	1853	-11.4	2.0	Taylors Pond
Muddy Creek	2872	874	-4.1	0.7	Lower Muddy Creek

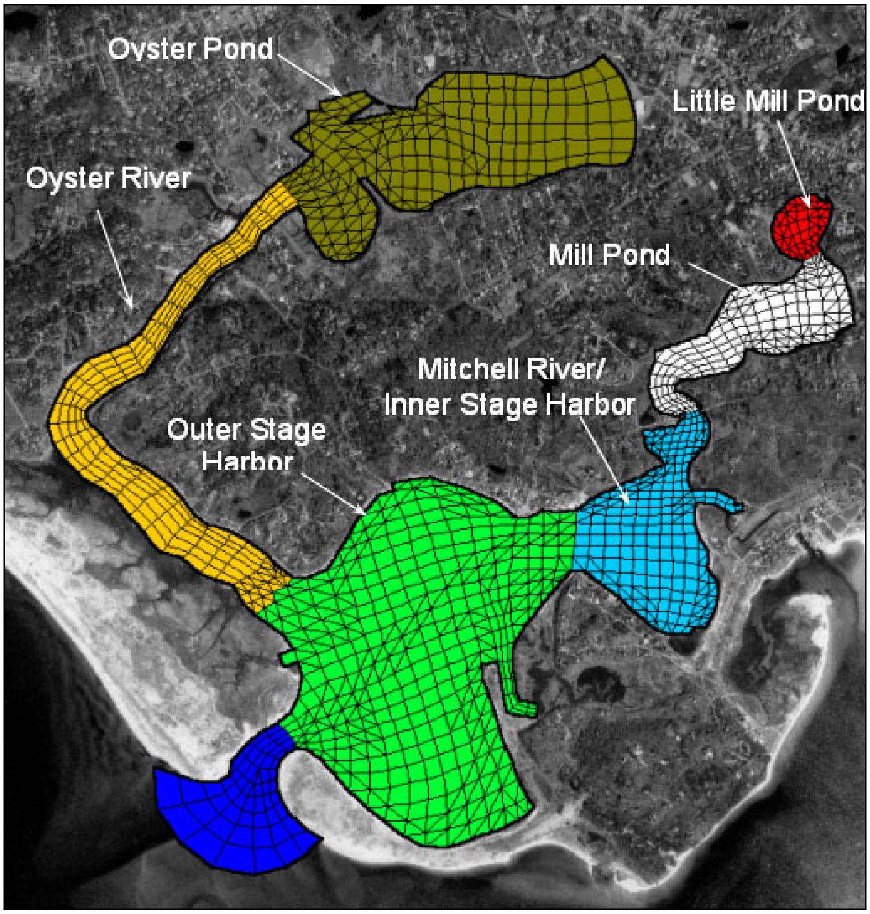

Figure V-40. Plot of numerical grid used for hydrodynamic modeling of Stage Harbor system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for individual embayments.

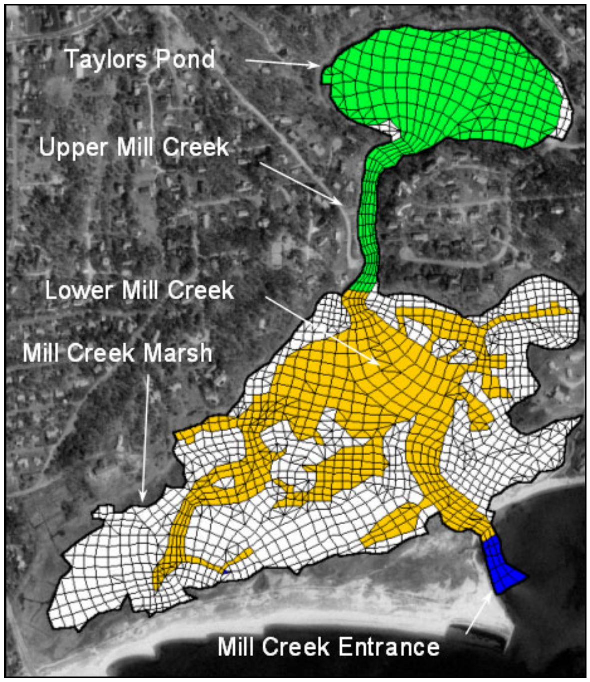

Figure V-41. Plot of numerical grid used for hydrodynamic modeling of Taylors Pond/Mill Creek system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for individual embayments.

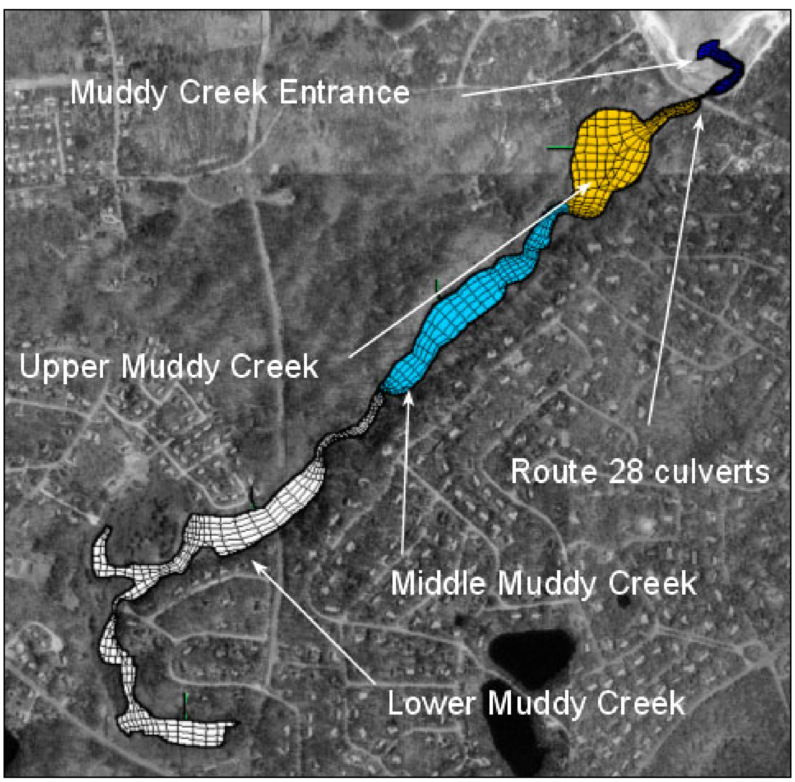

Figure V-42. Plot of numerical grid used for hydrodynamic modeling of Muddy Creek system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for the system.

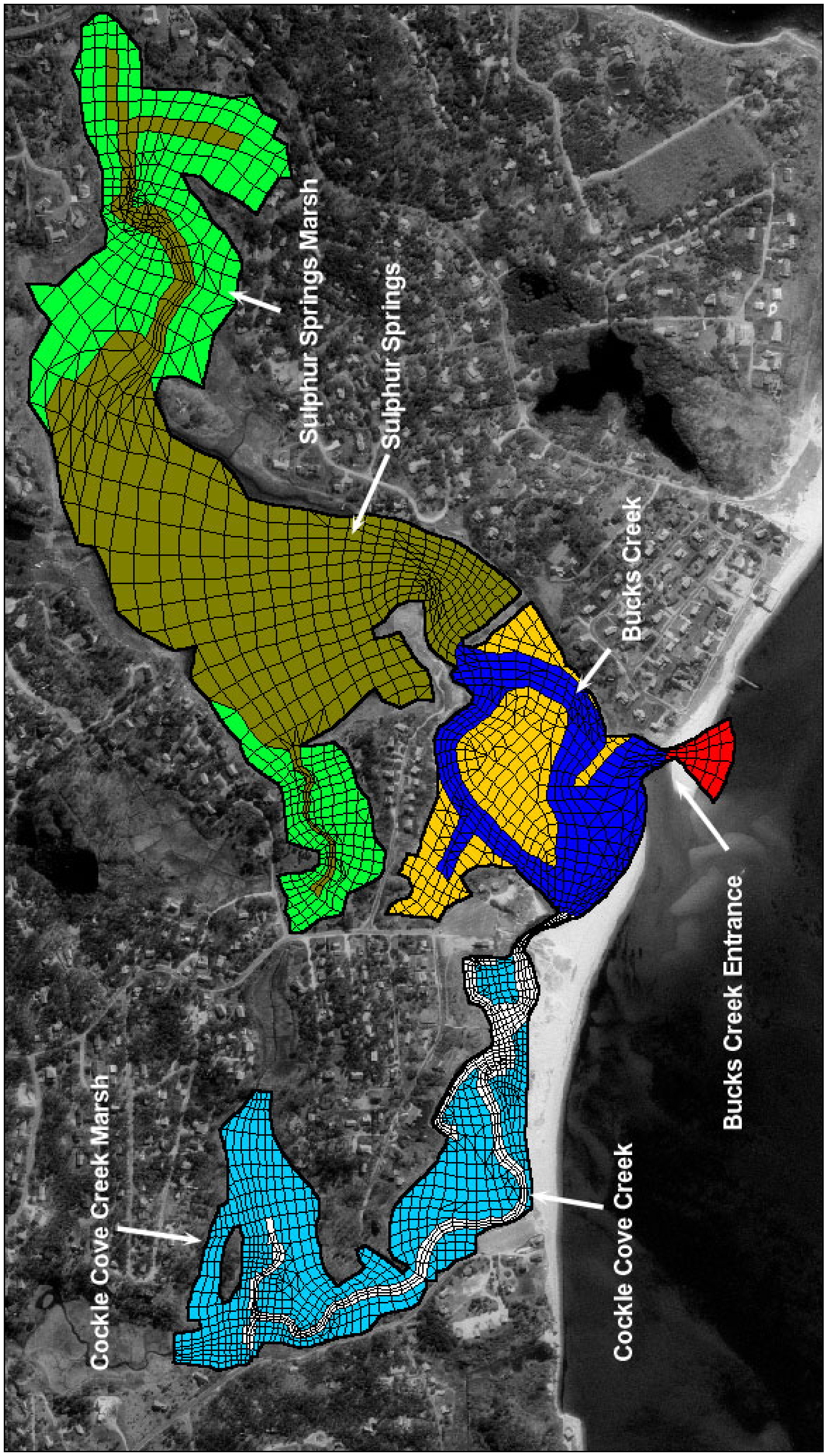

Figure V-43. Rotated view of numerical grid used for hydrodynamic modeling of Stage Harbor system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for individual embayments.

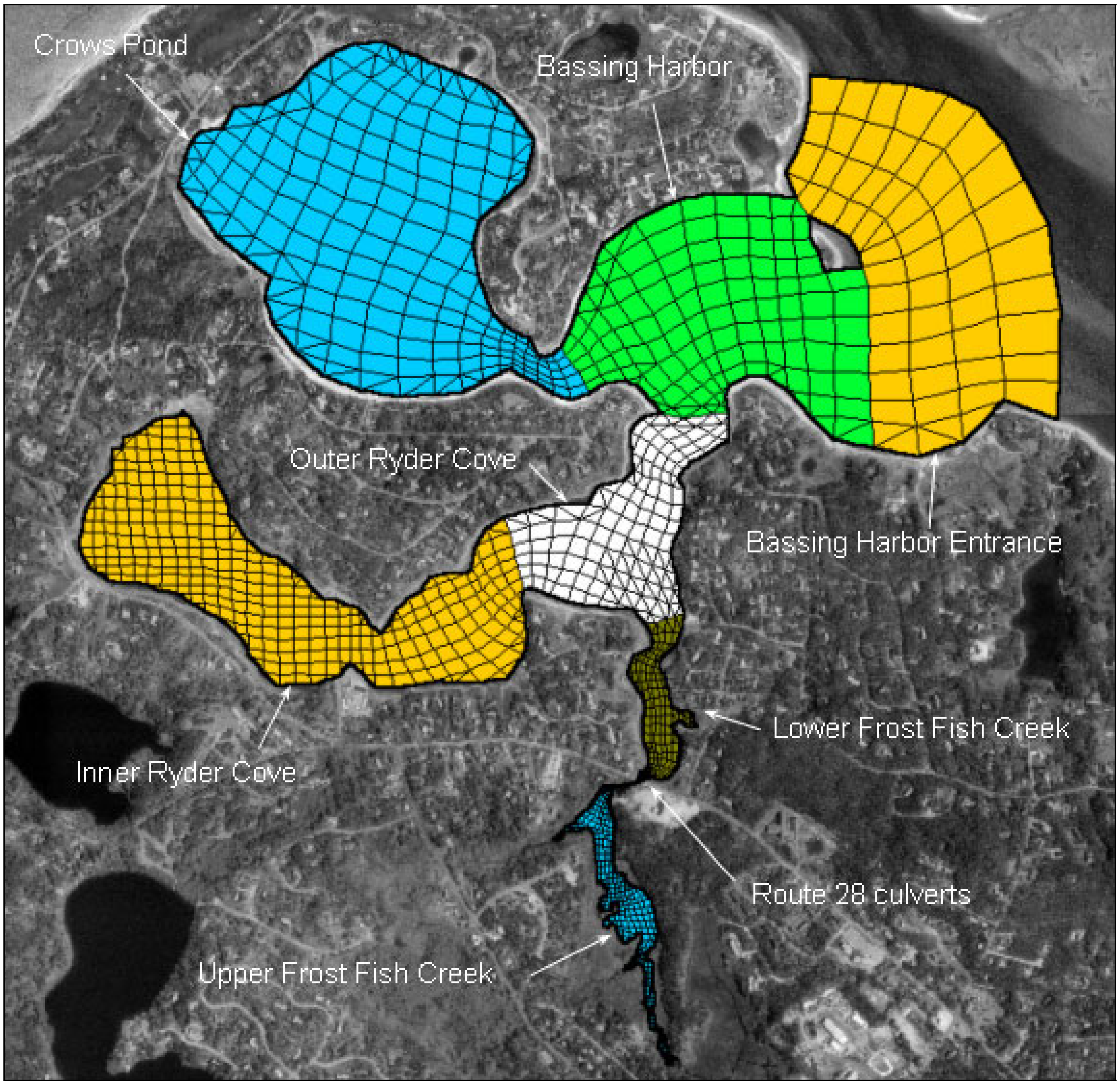

Figure V-44. Plot of numerical grid used for hydrodynamic modeling of Bassing Harbor system. Colored divisions indicate boundaries of different grid material types, as well as volumes used to compute flushing rates for individual embayments.

V.4.2.2 Boundary condition specification

Three types of boundary conditions were employed for the RMA-2V model: 1) "slip" boundaries, 2) freshwater inflow, and 3) tidal elevation boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. Based on watershed areas and average rainfall, freshwater recharge (surface and ground water flows) was specified for Muddy Creek and Frost Fish Creek. The flow rates used in the model are 1.56 ft3/sec for Frost Fish Creek and 3.43 ft3/sec for Muddy Creek, based on an average rainfall of 16 inch/year (Cape Cod Commission, 1998) and watershed areas determined using the Town GIS (849 acres for Frost Fish Creek and 1863 acres for Muddy Creek). A tidal boundary condition was specified seaward of the inlet to each system. TDR measurements provided the required data. The rise and fall of the tide in Nantucket Sound and

Pleasant Bay is the primary driving force for estuarine circulation. Dynamic (time-varying) model simulations specified a new water surface elevation in Nantucket Sound (for Stage Harbor, Sulphur Springs, and Taylors Pond), and Pleasant Bay (for Bassing Harbor and Muddy Creek) every model time step minutes (12 minutes).

V.4.2.3 Calibration

After developing the finite element grids, and specifying boundary conditions, the model for each system was calibrated. The calibration procedure ensures that the model predicts accurately what was observed in nature during the field measurement program. Calibrated models provide a diagnostic tool to evaluate other scenarios (e.g., the effects of increasing the size of the Frost Fish Creek culverts to improve flushing). Numerous model simulations were required (typically 15+) for each estuary, specifying a range of friction and eddy viscosity coefficients, to calibrate the model.

Calibration of the flushing model required a close match between the modeled and measured tides in each of the sub-embayments where tides were measured (i.e., from the TDR deployments). Initially, a two-day period was calibrated to obtain visual agreement between modeled and measured tides. Once visual agreement was achieved, a seven-day period was modeled to calibrate the model based on dominant tidal constituents discussed in Section III. The seven-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions.

The calibration was performed for a seven-day period beginning August 25, 2000 at 1800 EDT for the Pleasant Bay systems (i.e., Bassing Harbor and Muddy Creek), and beginning July 25, 2000 at 1600 EDT for the systems on Nantucket Sound (i.e., Stage Harbor, Sulphur Springs, and Taylors Pond). These representative time periods include the spring tide range of conditions, when the tide range largest, and resulting tidal currents are greater as well. To provide average tidal forcing conditions for the flushing analyses, a separate time period was chosen that spanned the transition between spring and neap tide ranges (bi-weekly maximum and minimum tidal ranges, respectively). For the flushing analysis the 7.25 day period (14 tide cycles) beginning July 31 2000, at 1300 EDT was used for the systems on Nantucket Sound, and a similar period beginning August 31 2000 at 0300 EDT was selected for the systems on Pleasant Bay.

The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire seven-day simulation. Other methods, such as dye and salinity studies, evaluate tidal flushing over relatively short time periods (less than one day). These short-term measurement techniques may not be representative of average conditions due to the influence of unique, short-lived atmospheric events. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated model was used to analyze existing detailed flow patterns and compute residence times.

V.4.2.3.1 Friction coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2V as a Manning coefficient. Initially, Manning's friction coefficients between 0.02 and 0.07 were specified for all elements. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels and marsh plains with higher friction (Henderson, 1966).

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning's coefficients were matched to bottom type. For example, lower friction coefficients were specified for the smooth sandy channels in the entrance channel of each Pond, versus the silty bottom of the shallow regions in the upper portions of each Pond, which provided greater flow resistance. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992), and values were incrementally changed when necessary to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-8.

V.4.2.3.2 Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 50 and 100 lb-sec/ft2. Higher values (up to 300 lb-sec/ft2) were used on the marsh plain and in culverts.

V.4.2.3.3 Wetting and Drying/marsh porosity processes

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh plain as well as in intertidal regions in each of the systems. In the case of the marsh plains that are a part of the Sulphur Springs/Cockle Cove Creek and Mill Creek systems, wet/dry areas will tend to store waters as the tide begins to ebb and then slowly release water as the water level drops within the creeks and channels. This store-and-release characteristic of these marsh regions was partially responsible for the distortion of the tidal signal, and the elongation of the ebb phase of the tide. On the flood phase, water rises within the channels and creeks initially until water surface elevation reaches the marsh plain, when at this point the water level remains nearly constant as water 'fans' out over the marsh surface. The rapid flooding of the marsh surface corresponds to a flattening out of the tide curve approaching high water. Marsh porosity is a feature of the RMA-2V model which permits the modeling of hydrodynamics in marshes. This model feature essentially simulates the store-and-release capability of the marsh plain by allowing grid elements to transition gradually between wet and dry states. This technique allows RM-2V to change the ability of an element to hold water, like squeezing a sponge. The marsh porosity feature of RMA-2V is typically utilized in estuarine systems where the marsh plain has a significant impact on the hydrodynamics of a system, such as Sulphur Springs and Mill Creek.

Table V-8. Manning's Roughness coefficients used in simulations of modeled embayments.		
System	Embayment	Bottom Friction
Stage Harbor	Stage Harbor Entrance	0.030
	Lower Stage Harbor	0.030
	Mitchell River / Upper Stage Harbor	0.030
	Mill Pond	0.025
	Little Mill Pond	0.025
	Oyster Pond River	0.030
	Oyster Pond	0.030
Sulphur Springs	Bucks Creek Entrance	0.030
	Bucks Creek	0.030
	Sulphur Springs	0.030
	Sulphur Springs Marsh Plain	0.100
	Cockle Cove Creek	0.040
	Cockle Cove Creek Marsh Plain	0.070
Taylors Pond	Mill Creek Entrance	0.030
	Taylors Pond	0.025
	Mill Creek	0.027
	Mill Creek Marsh Plain	0.100
Bassing Harbor	Bassing Harbor Entrance	0.030
	Bassing Harbor	0.031
	Outer Ryder Cove	0.015
	Crows Pond	0.030
	Inner Ryder Cove	0.015
	Upper Frost Fish Creek	0.030
	Frost Fish Creek culverts	0.500
	Lower Frost Fish Creek	0.030
Muddy Creek	Muddy Creek Entrance	0.030
	Muddy Creek Culverts	0.150
	Muddy Creek	0.025

For Stage Harbor and Bassing Harbor, an alternate method was employed to simulate the periodic inundation and drying of tidal flats in these systems. Nodal wetting and drying is a feature of RMA-2V that allows grid elements to be removed and re-inserted during the course of the model run. Figure V-45 presents an example of how the computational grid is modified by element elimination. This figure shows the Stage Harbor model at a point just after low tide. White areas within the boundary of the mesh are elements that have gone dry, and as a result, have been removed temporarily from the model solution. The wetting and drying feature has two keys benefits for the simulation, 1) it enhances the stability of the model by eliminating nodes that have bottom elevations that are higher than the water surface elevation at that time, and 2) it reduces total model run time because node elimination can reduce the size of the computational grid significantly during periods of a model run. Wetting and drying is employed for estuarine systems with relatively shallow borders and/or tidal flats.

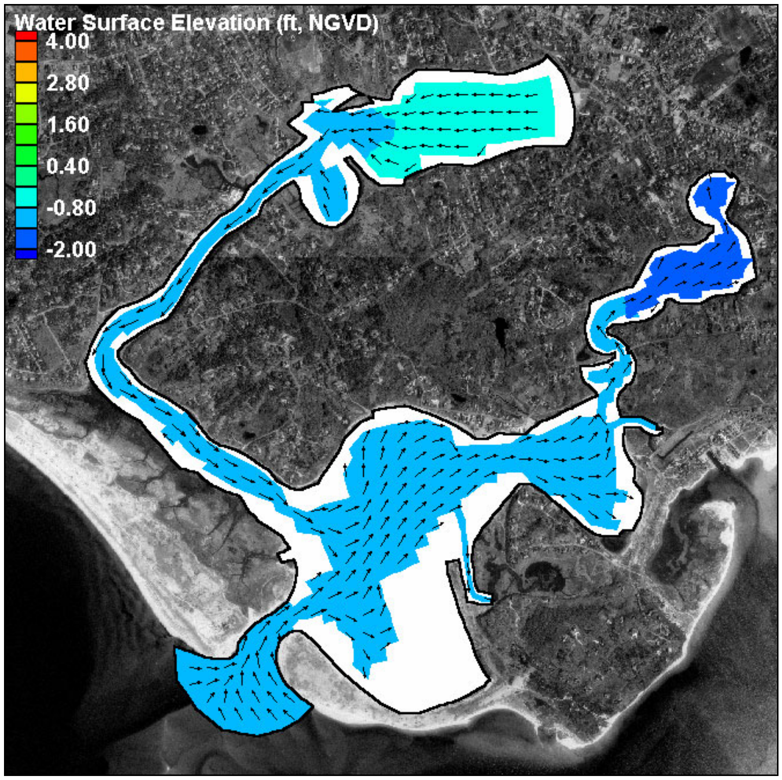

Figure V-45. Stage Harbor model at the inception of a flood tide, with white areas indicating dry elements.

V.4.2.3.4 Comparison of modeled tides and measured tide data

A best-fit of model predictions for the first TDR deployment was achieved using the aforementioned values for friction and turbulent exchange. Figures V-46 through V-54 illustrate the seven-day calibration simulation along with a two-day sub-section. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the modeled systems. Due to the duration of the model runs, four dominant tidal constituents were selected for constituent comparison: K_1, M_2, M_4, and M_6. Measured tidal constituent heights (H) and time lags (ϕ_{lag}) shown in Tables V-9 and V-4 for the calibration period differ from those in Table V-7 because constituents were computed for only the seven-day section of the thirty-days represented in Table V-7. Tables V-9 and V-10 compare tidal constituent height and time lag for modeled and measured tides at the TDR locations. Time lag represents the time required for a constituent to propagate from offshore (Nantucket Sound or Pleasant Bay) to each TDR location.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were on the order of 0.1 ft, which was only slightly larger than the accuracy of the tide gages (0.032 ft). Generally, errors in modeled constituent amplitudes were of the order 0.01 ft. Time lag errors were typically less than the time increment resolved by the model (0.20 hours or 12 minutes), indicating good agreement between the model and data.

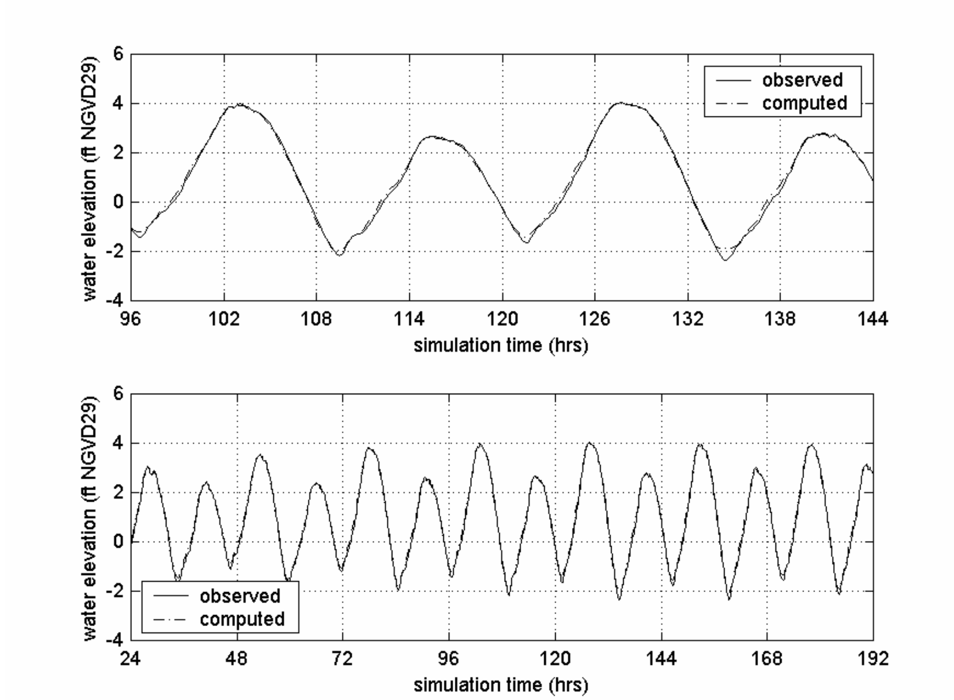

Figure V-46. Observed and computed water surface elevations during calibration time period, for Mill Pond.

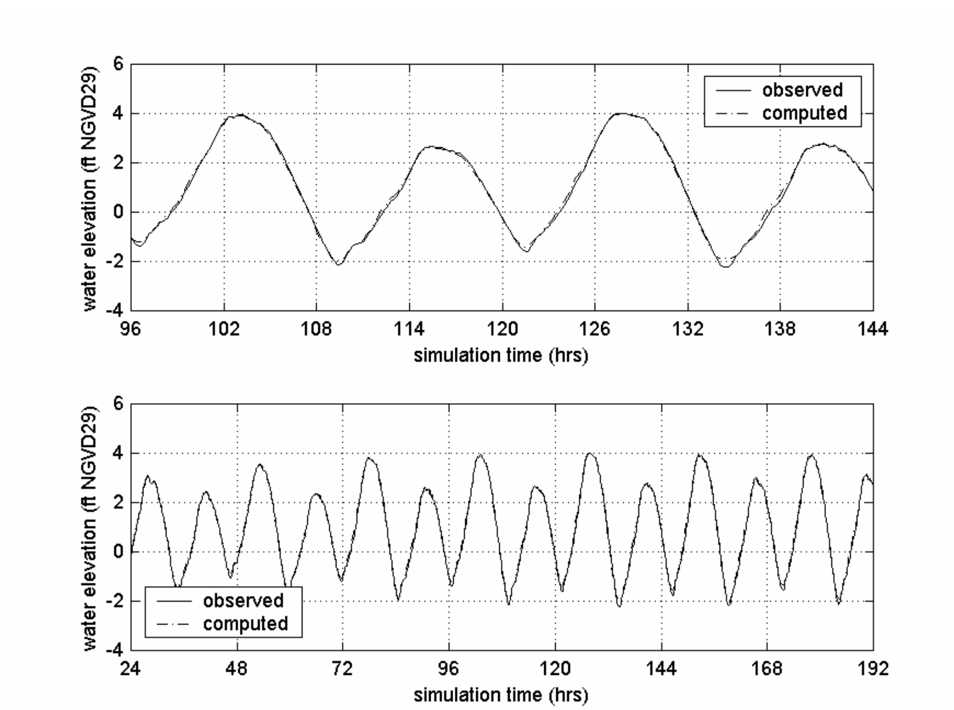

Figure V-47. Observed and computed water surface elevations during calibration time period, for Little Mill Pond.

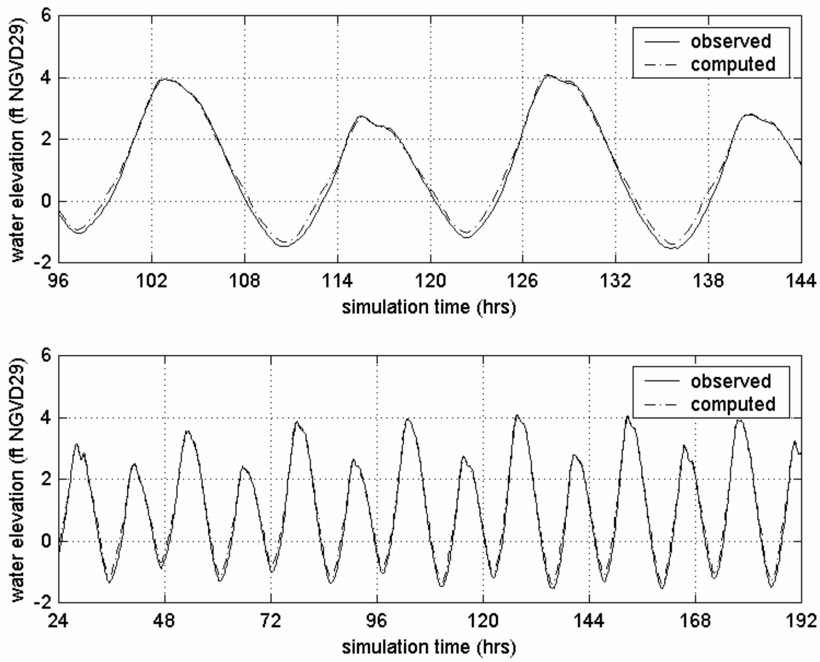

Figure V-48. Observed and computed water surface elevations during calibration time period, for Oyster Pond.

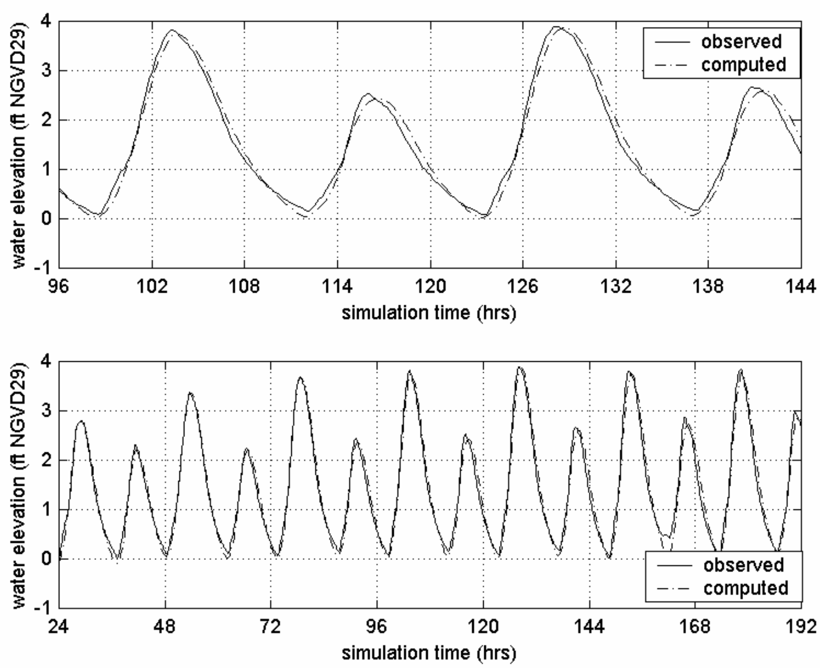

Figure V-49. Observed and computed water surface elevations during calibration time period, for Sulphur Springs.

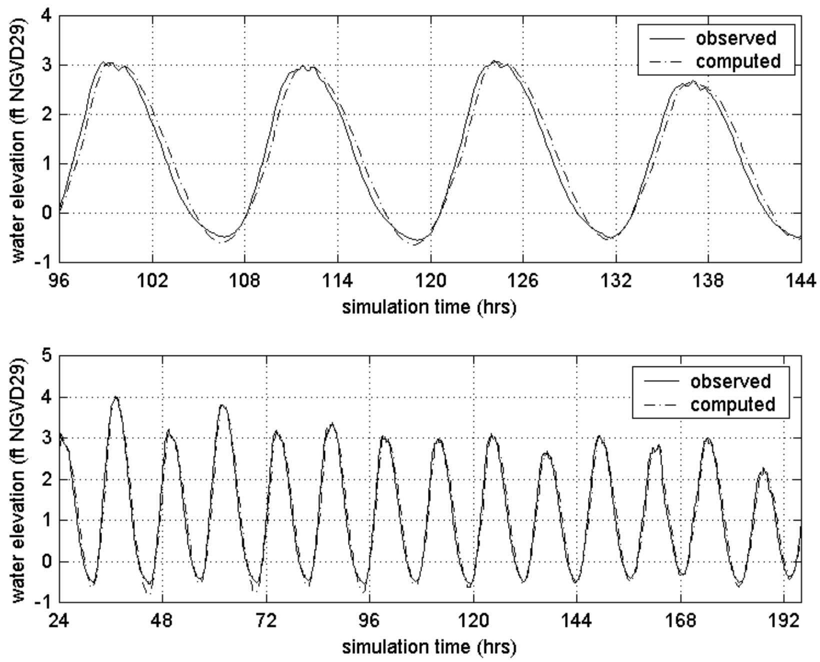

Figure V-50. Observed and computed water surface elevations during calibration time period, for Taylors Pond.

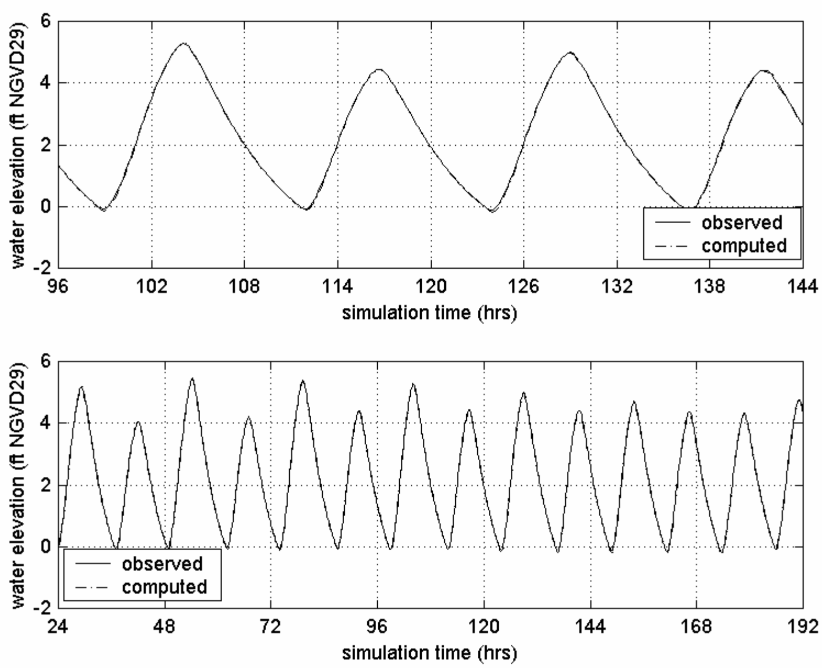

Figure V-51. Observed and computed water surface elevations during calibration time period, for Crows Pond.

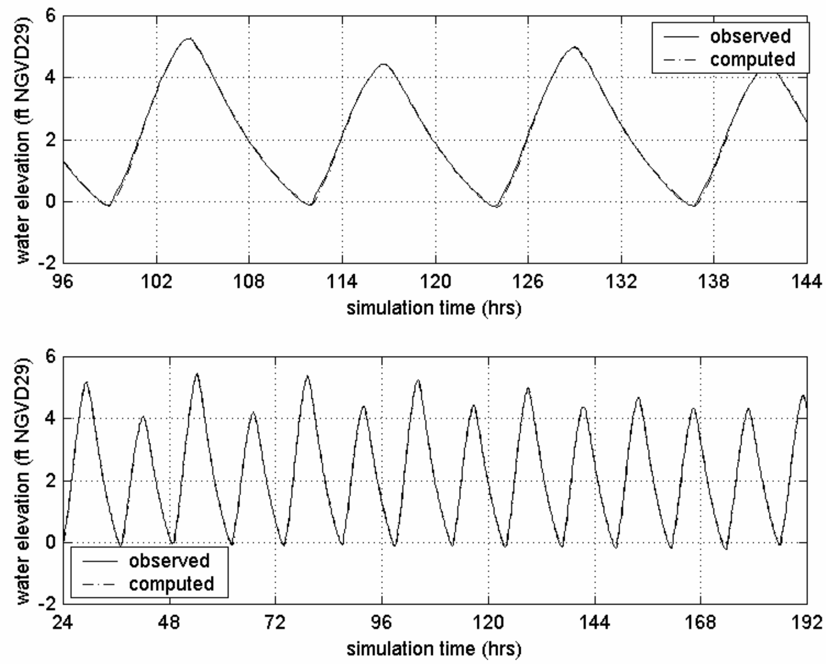

Figure V-52. Observed and computed water surface elevations during calibration time period, for Ryder Cove.

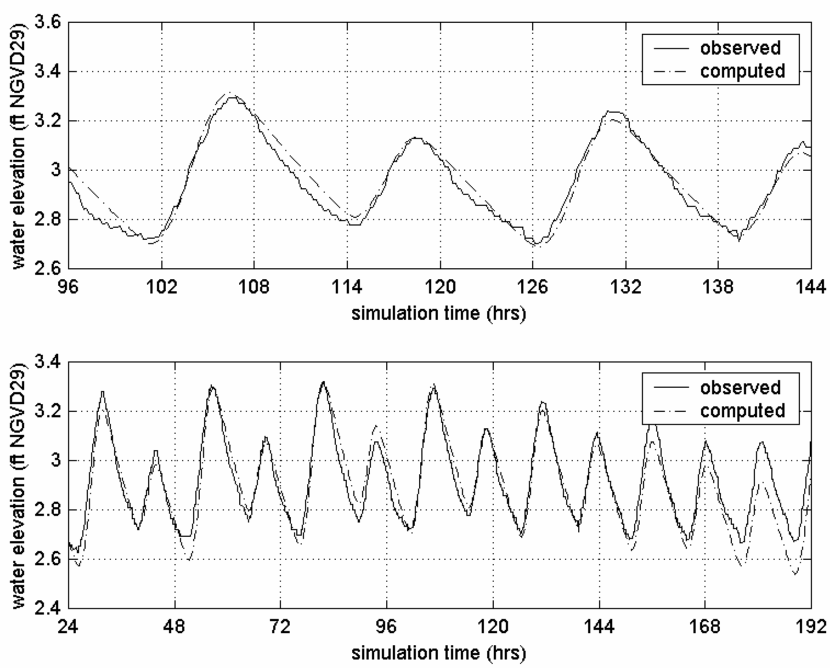

Figure V-53. Observed and computed water surface elevations during calibration time period, for Frost Fish Creek.

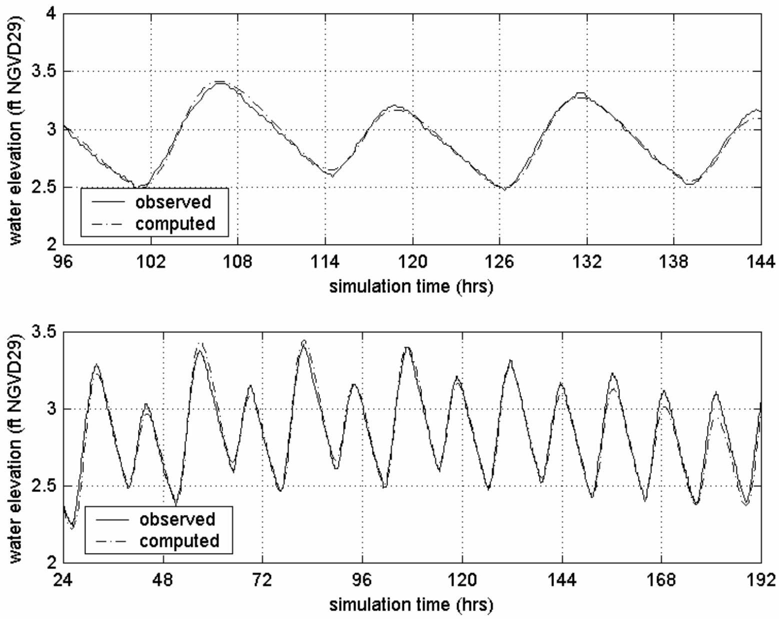

Figure V-54. Observed and computed water surface elevations during calibration time period, for Muddy Creek.

Table V-9. Tidal constituents for measured water level data and calibrated model output for northern embayments.						
Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Crows Pond	2.17	0.37	0.06	0.30	171.2	267.3
Ryder Cove	2.17	0.35	0.07	0.30	170.2	265.4
Frost Fish Creek	0.20	0.05	0.01	0.08	247.0	34.3
Muddy Creek	0.33	0.05	0.01	0.11	251.0	19.3
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Crows Pond	2.16	0.36	0.05	0.30	170.9	266.9
Ryder Cove	2.16	0.32	0.07	0.30	168.9	263.6
Frost Fish Creek	0.20	0.04	0.01	0.08	237.8	43.6
Muddy Creek	0.33	0.06	0.01	0.10	246.9	25.5
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Crows Pond	0.01	0.01	0.01	0.00	0.6	0.4
Ryder Cove	0.01	0.02	0.00	0.00	2.8	1.8
Frost Fish Creek	0.00	0.01	0.00	0.00	19.0	9.7
Muddy Creek	0.00	0.01	0.00	0.01	8.6	6.4

Table V-10. Tidal constituents for measured water level data and calibrated model output for Stage Harbor and South Coast Embayments.

Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Mill Pond	2.24	0.13	0.12	0.57	140.6	81.0
Little Mill Pond	2.24	0.13	0.12	0.57	140.7	82.1
Oyster Pond	2.16	0.14	0.07	0.56	153.9	214.7
Sulphur Springs	1.40	0.23	0.03	0.48	171.7	278.3
Taylors Pond	1.80	0.18	0.06	0.16	152.4	245.7
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Mill Pond	2.30	0.13	0.13	0.57	142.4	85.7
Little Mill Pond	2.31	0.13	0.14	0.57	142.7	86.3
Oyster Pond	2.03	0.14	0.07	0.57	155.1	222.1
Sulphur Springs	1.35	0.28	0.05	0.48	164.6	277.8
Taylors Pond	1.82	0.14	0.04	0.17	149.3	243.2
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Mill Pond	**0.06**	0.00	0.01	0.00	3.7	4.9
Little Mill Pond	0.07	0.00	0.02	0.00	4.2	4.3
Oyster Pond	0.13	0.00	0.00	0.01	2.5	7.7
Sulphur Springs	0.05	0.05	0.02	0.00	14.8	0.4
Taylors Pond	0.02	0.04	0.02	0.01	6.5	10.5

The hydrodynamic model's ability to predict propagation of the secondary non-linear constituents through the estuary is important for understanding the attenuation of the tidal signal and the impact this has on estuarine circulation. Of primary interest is the M_4 constituent, which can be used to determine the flood dominance (sediment trapping characteristics) of an estuarine system. Proper prediction of M_4 provides confidence in the model's accuracy, since this indicates that the model is capable of simulating the tidal wave form and size. Similar to the model predictions for M_2, comparison of the information from Tables V-9 and V-10 indicates that the modeled phase of M_4 falls within one time step of the observed value.

V.4.3 Model Verification Using ADCP Measurements

The calibration procedure used in the development of the five separate finite-element models required a match between measured and modeled tides. To verify the performance of the Stage Harbor and Bassing Harbor models, computed flow rates were compared to flow rates measure using an ADCP. The ADCP data survey efforts are described in Chapter III. For model verification, both models were run for the period covered during each ADCP survey, on August 16 for Stage Harbor, and September 1 for Bassing Harbor. Model flow rates were computed in RMA-2V at continuity lines (channel cross-sections) that correspond to the actual ADCP transects followed in each survey.

V.4.3.1 Stage Harbor

A comparison of the measured and computed volume flow rates at the Stage Harbor Inlet is shown in Figure V-55 in the top plot, and the tide curve for the same time period is shown in the lower plot. Each ADCP point is a summation of flow measured along the ADCP transect. The ‘bumps’ and ‘skips’ of the flow rate curve can be attributed to the effects of winds (i.e., atmospheric effects) on the water surface and friction across the seabed periodically retarding or accelerating the flow through the inlet, and in the harbor. If water surface elevations changed smoothly as a sinusoid, the volume flow rate would also appear as a smooth curve. However, since the rate at which water surface elevations change does not vary smoothly, the flow rate curve is expected to show short-period fluctuations.

Figure V-55 for the Stage Harbor inlet shows a remarkably good agreement with the model predictions. The calibrated model accurately describes the general conditions and the irregularities of the discharge through the Stage Harbor inlet. Again, at the mouth of Oyster Pond River (Figure IV-56) and the Mill Pond Bridge (Figure V-57), computed volume flow rates agree well with the field measurements, even though the flows are an order of magnitude (~10 times) smaller at the Mill Pond Bridge than in Stage Harbor. Currents are more difficult to accurately measure with the ADCP along the Mill Pond Bridge and Oyster Pond River transects, since these areas are considerably shallower than the harbor inlet. Therefore, portions of the channels are not covered by the ADCP because 1) the ADCP draft (no measurements in top layer), and 2) tide flats too shallow to safely navigate the survey boat, become a much more significant source of measurement error.

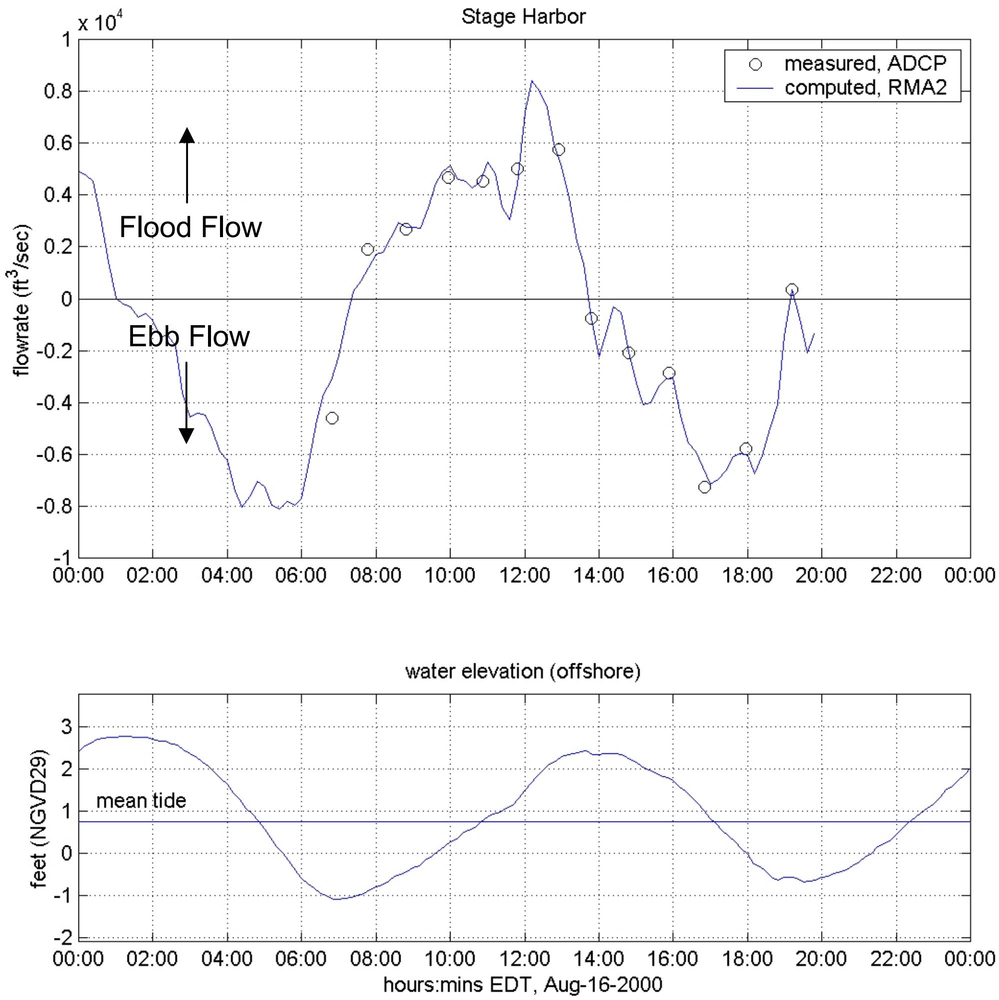

Figure V-55. Comparison of measured volume flow rates versus modeled flow rates through the Stage Harbor Inlet over a tidal cycle on August 16, 2000. Flood flows into the harbor are positive (+), and ebb flows out of the harbor are negative (-).

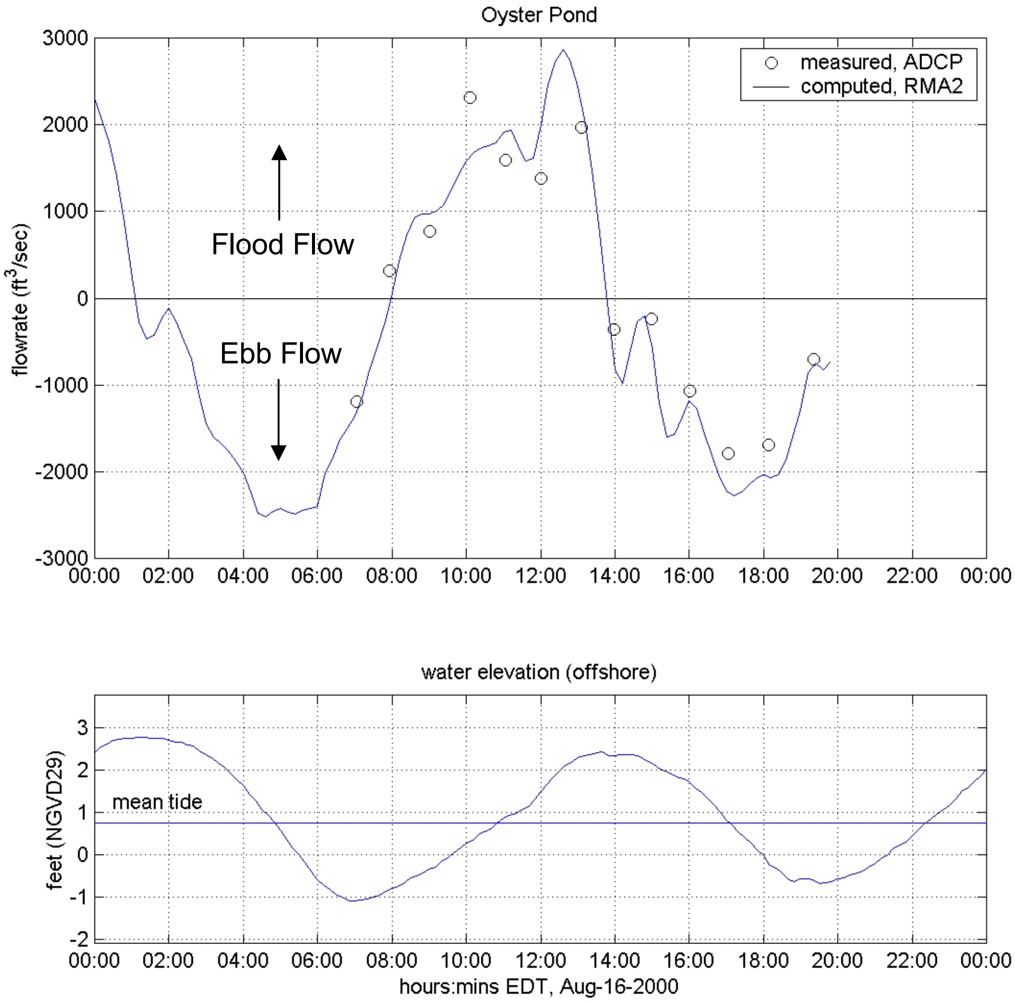

Figure V-56. Comparison of measured volume flow rates versus modeled flow rates through the mouth of Oyster Pond River over a tidal cycle on August 16, 2000. Flood flows into the river are positive (+), and ebb flows out of the river are negative (-).

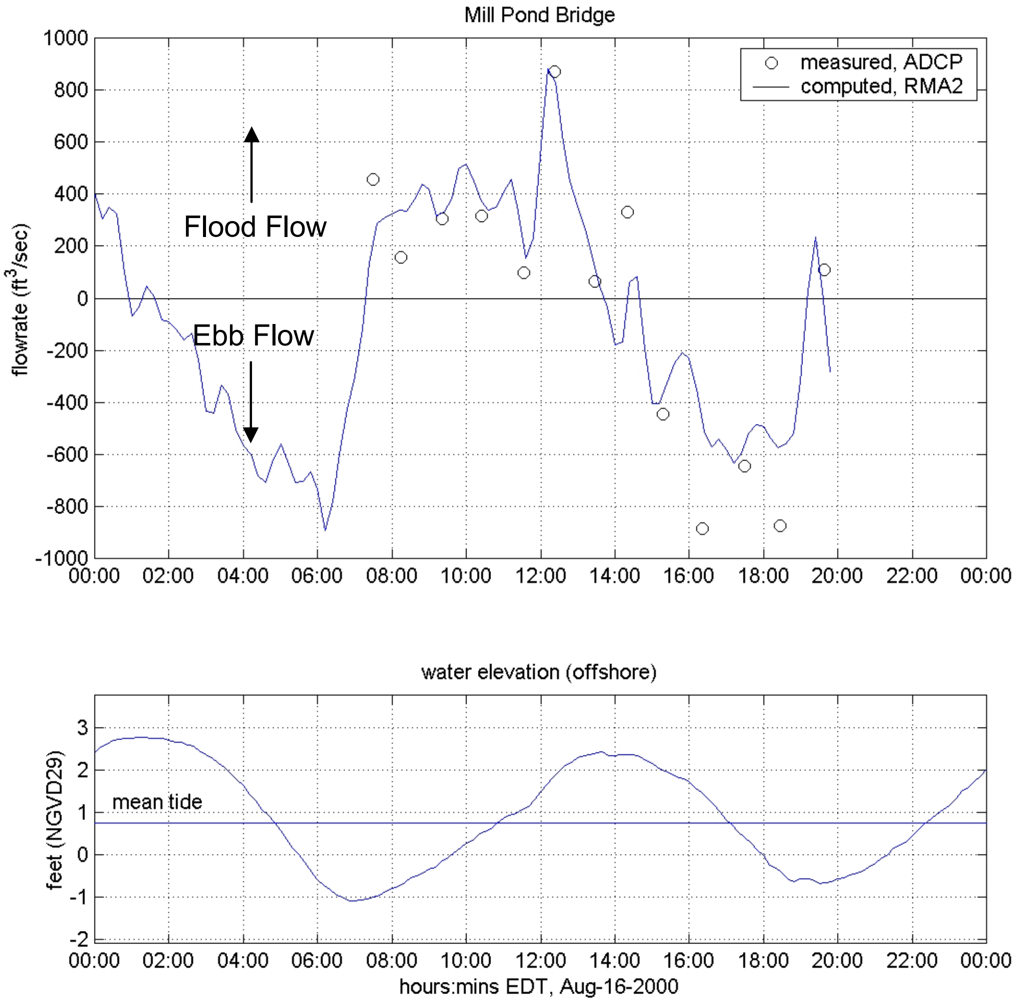

Figure V-57. Comparison of measured volume flow rates versus modeled flow rates through the Mill Pond Bridge over a tidal cycle on August 16, 2000. Flood flows into the pond are positive (+), and ebb flows out of the pond are negative (-).

V.4.3.2 Bassing Harbor

The calibrated Bassing Harbor model was utilized to compute volume flow rates for the mouth of Bassing Harbor, Ryder Cove (including Frost Fish Creek), and Crows Pond. The overall shape of the volume flow curve at the entrance to Bassing Harbor is relatively smooth compared to the Stage Harbor curve, suggesting that wind had less influence on water level changes for this system during the survey period. Flow rates at the Bassing Harbor inlet were noticeably over-predicted during ebb flows (Figure V-58).

The apparent large difference (~20%) during ebbing flow may result from the fact that the ADCP survey transect at the mouth of Bassing Harbor crossed between the southern shore of the inlet and Fox Hill to the north, and not completely across the harbor entrance. Fox Hill is an island, and is connected to the northern shore of the harbor mouth by a sand spit, which is submerged during much of the tide cycle. During the period of the tide cycle following high tide, water can flow easily over this spit. However, during the period following low tide, the spit is barely submerged, resulting in much less flow in this area of the harbor mouth. Therefore, measured and modeled flow rates agree better during the flood flow, when nearly all the flow into Bassing Harbor occurs between Fox Hill and the southern shore of the harbor entrance.

Water moving through Bassing Harbor is divided between Ryder Cove/Frost Fish Creek and Crows Pond. The computed volume flow rates from the calibrated model closely reflect the measured flow rates in the sub-embayments of Bassing Harbor (Figure V-59 and V-60).

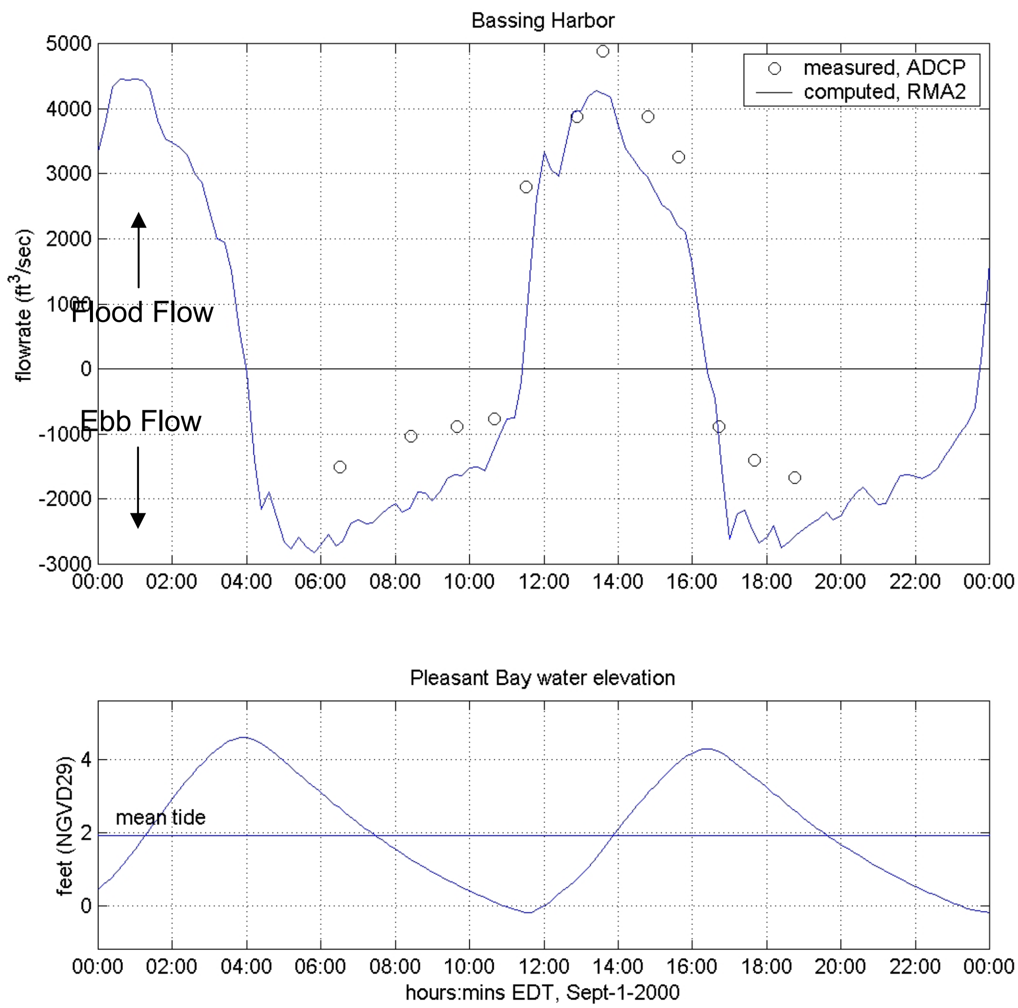

Figure V-58. Comparison of measured volume flow rates versus modeled flow rates through the Bassing Harbor Inlet over a tidal cycle on September 1, 2000. Flood flows into the harbor are positive (+), and ebb flows out of the harbor are negative (-).

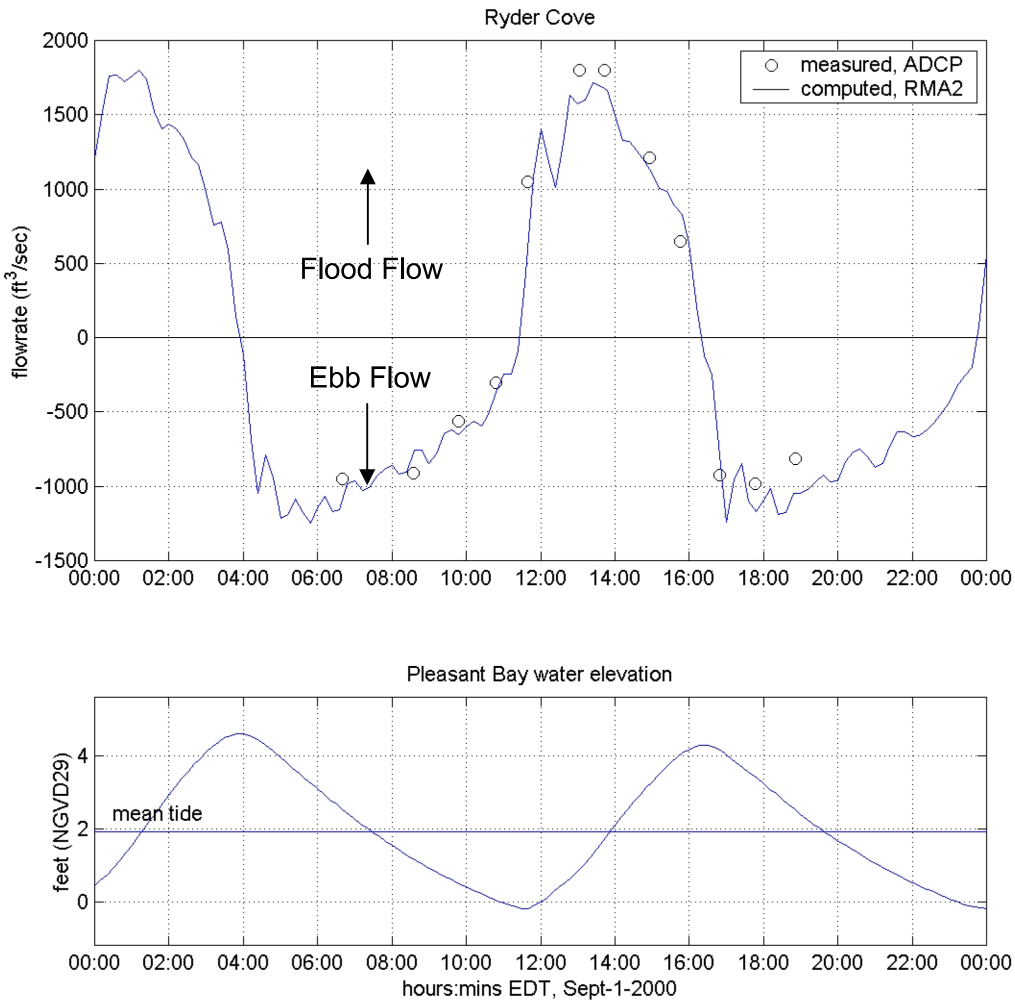

Figure V-59. Comparison of measured volume flow rates versus modeled flow rates through the entrance to Ryder Cove/Frost Fish Creek over a tidal cycle on September 1, 2000. Flood flows into the cove are positive (+), and ebb flows out of the cove are negative (-).

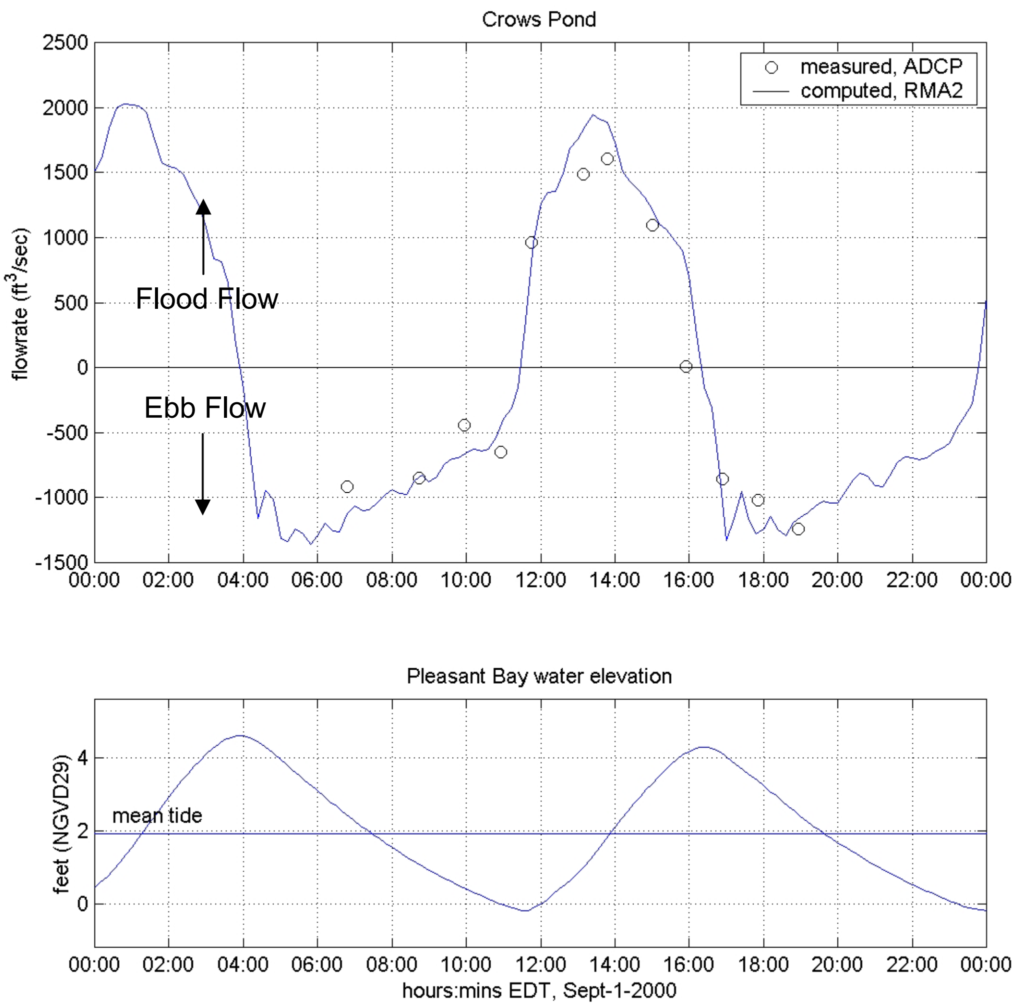

Figure V-60. Comparison of measured volume flow rates versus modeled flow rates through the mouth of Crows Pond over a tidal cycle on September 1, 2000. Flood flows into the pond are positive (+), and ebb flows out of the pond are negative (-).

V.5 FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through each inlet, the primary mechanism controlling estuarine water quality within each of the modeled systems is tidal exchange. An exception in this study is Frost Fish Creek, where estimated groundwater inflow into the creek is slightly greater than 50% of the average tidal exchange through the Route 28 culverts, based on the average tidal flow 2.8 ft^3/sec (125,200 ft^3 per tide cycle) and estimated freshwater input of 1.6 ft^3/sec (annual average). A rising tide offshore in Nantucket Sound or Pleasant Bay creates a slope in water surface from the ocean into the modeled systems. Consequently, water flows into (floods) the system. Similarly, each estuary drains into the open waters of Nantucket Sound or Pleasant Bay on an ebbing tide. This exchange of water between each system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of each system, and was used to compute flushing rates (residence times) and tidal circulation patterns.

V.5.1 Residence Times

Flushing rate, or residence time, is defined as the average time required for a parcel of water to migrate out of an estuary from points within the system. For this study, **system residence times** were computed as the average time required for a water parcel to migrate from a point within the each embayment to the entrance of the system. System residence times are computed as follows:

$$T_{system} = \frac{V_{system}}{P} t_{cycle}$$

where T_{system} denotes the residence time for the system, V_{system} represents volume of the (entire) system at mean tide level, P equals the tidal prism (or volume entering the system through a single tidal cycle), and t_{cycle} the period of the tidal cycle, typically 12.42 hours (or 0.52 days). To compute system residence time for a sub-embayment, the tidal prism of the sub-embayment replaces the total system tidal prism value in the above equation.

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using Crows Pond as an example, the **system residence time** is the average time required for water to migrate from Crows Pond, through Bassing Harbor, and into Pleasant Bay, where the **local residence time** is the average time required for water to migrate from Crows Pond to Bassing Harbor. Local residence times for each sub-embayment are computed as:

$$T_{local} = \frac{V_{local}}{P} t_{cycle}$$

where T_{local} denotes the residence time for the local sub-embayment, V_{local} represents the volume of the sub-embayment at mean tide level, P equals the tidal prism (or volume entering the local sub-embayment through a single tidal cycle), and t_{cycle} the period of the tidal cycle (again, 0.52 days).

Residence times are provided as a first order evaluation of estuarine water quality. Lower residence times generally correspond to higher water quality; however, residence times may be misleading depending upon pollutant/nutrient loading rates and the overall quality of the receiving waters. As a qualitative guide, **system residence times** are applicable for systems where the water quality within the entire estuary is degraded and higher quality waters provide the only means of reducing the high nutrient levels. For the Stage Harbor Region estuaries this approach is applicable, since it assumes the main system has relatively low quality water relative to Nantucket Sound.

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. Efficient tidal flushing (low residence time) is not an indication of high water quality if pollutants and nutrients are loaded into the estuary faster than the tidal circulation can flush the system. Neither are low residence times an indicator of high water quality if the water flushed into the estuary is of poor quality. Advanced understanding of water quality will be obtained from the calibrated hydrodynamic model by extending the model to include pollutant/nutrient dispersion. The future water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Stage Harbor System, South Coast Embayments, and Pleasant Bay Region estuaries.

Since the calibrated RMA-2 model simulated accurate two-dimensional hydrodynamics in each estuary, model results were used to compute residence times. Residence times were computed for the entire estuary, as well as several sub-embayments within the estuary. In addition, **system** and **local residence times** were computed to indicate the range of conditions possible for each of the estuarine systems. Residence times were calculated as the volume of water (based on the mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days. The volume of the entire estuary was computed as cubic feet. Residence times were averaged for the tidal cycles comprising the representative 7.25 day period (14 tide cycles), and are listed in Table V-12. Model divisions used to define the system sub-embayments listed in Tables V-11 and V-12 are shown in Figures V-61 through Figure V-65, in the previous section. The model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume.

Generally, errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. Since the calibration period represented average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the various sub-embayments. The bathymetry data collection effort focused on regions of rapidly changing flow conditions (flow constrictions). This methodology provided an efficient and economical technique to measure bathymetric fluctuations affecting tidal flushing; however, the limited bathymetry survey associated with this study may have missed some shoals and/or deep holes introducing minor errors into the residence time calculations. In addition, limited topographic measurements were available on the extensive marsh plains of the South Coast Embayments.

Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle. For regions where a strong littoral drift exists, this assumption is valid. However, water exiting a small sub-embayment on a relatively calm day may not completely mix with estuarine waters. In this case, the “strong littoral drift” assumption would lead to an under-prediction of residence time. Since littoral drift along the Nantucket Sound and Pleasant Bay shorelines in Chatham typically is strong and local winds induce tidal mixing within the regional estuarine systems, the "strong littoral drift" assumption only will cause minor errors in residence time calculations. Based on our knowledge of estuarine processes, we estimate that the combined errors due to bathymetric inaccuracies represented in the model grid and the "strong littoral drift" assumption are within 10% to 15% of "true" residence times.

Table V-11. Embayment mean volumes and average tidal prism during simulation period.

System	Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Stage Harbor	Stage Harbor (system)	142,825,500	107,176,900
	Mitchell R. / Upper Stage H.	40,210,100	20,729,200
	Mill Pond	19,067,900	8,349,300
	Little Mill Pond	3,394,400	1,312,400
	Oyster Pond River	42,797,000	35,598,500
	Oyster Pond	28,218,000	17,925,400
Sulphur Springs	Bucks Creek (system)	7,426,200	10,311,800
	Sulphur Springs	4,885,700	6,747,900
	Cockle Cove Creek	818,700	1,133,200
Taylors Pond	Mill Creek (system)	6,973,900	9,341,300
	Taylors Pond	3,145,600	2,003,100
Bassing Harbor	Bassing Harbor (system)	102,152,200	51,252,700
	Crows Pond	53,345,200	20,699,300
	Ryder Cove	19,385,600	12,805,800
	Frost Fish Creek	1,414,500	1,230,000
	Upper Frost Fish Creek	727,800	125,200
	Ryder Cove / Frost Fish Creek	30,338,500	18,967,900
Muddy Creek	Muddy Creek (system)	5,699,300	982,900

The relatively long residence time for a sub-embayment such as Cockle Cove Creek reveals the inadequacy of using system residence time alone to evaluate water quality. The system residence time is computed as 3.4 days, even though this marsh creek nearly goes dry at low tide. By the definition of system residence time, smaller sub-embayments have longer residence times; therefore, residence times may be misleading for small, remote parts of the estuary. Instead, it is useful to compute a local residence time for each sub-embayment. A local residence time represents the time required for a water parcel to leave the particular sub-embayment. For instance, the local residence time for Upper Frost Fish Creek represents the time required for a water parcel to be flushed from the upper portion of the creek into lower Frost Fish Creek. Local residence times are computed as the volume of the sub-embayment divided by the tidal prism of that sub-embayment, and units are converted to days. Table V-12 lists local residence times for several areas within each of the modeled systems.

Local residence times in Table V-12 are significantly lower than residence times based on the volume of the entire estuary. For example, flow entering Little Mill Pond on an average tidal cycle flushes through Stage Harbor inlet in 56.3 days, but flushes into Mill Pond in 1.3 days. Generally, a local residence time is only useful where the adjacent embayment has high water quality. For some of the embayments located in the upper reaches of each system (again, Mill

Pond and Frost Fish Creek), the receiving waters that exchange tidal flow with the various sub-embayments show signs of ecological stress, indicative of poor water quality. Therefore, system residence times may be more appropriate for future planning scenarios.

Table V-12. System and Local residence times (flushing rates) for Chatham sub-embayments.

System	Embayment	System Residence Time (days)	Local Residence Time (days)
Stage Harbor	Stage Harbor (system)	0.7	0.7
	Mitchell R. / Upper Stage H.	3.6	1.0
	Mill Pond	8.9	1.2
	Little Mill Pond	56.3	1.3
	Oyster Pond River	2.0	0.6
	Oyster Pond	4.1	0.8
Sulphur Springs	Bucks Creek (system)	0.4	0.4
	Sulphur Springs	0.6	0.4
	Cockle Cove Creek	3.4	0.4
Taylors Pond	Mill Creek (system)	0.4	0.4
	Taylors Pond	1.8	0.8
Bassing Harbor	Bassing Harbor (system)	1.0	1.0
	Crows Pond	2.6	1.3
	Ryder Cove	4.1	0.8
	Frost Fish Creek	43.0	0.6
	Upper Frost Fish Creek	422.3	3.0
	Ryder Cove / Frost Fish Creek	2.8	0.8
Muddy Creek	Muddy Creek (system)	3.0	3.0

Another important characteristic of system residence times is that values determined for each sub-embayment are directly dependent on what exactly the total system volume includes. This is readily apparent when a comparison of system residence time from the current report is made to values presented in previous flushing calculations for all of Pleasant Bay (ACI, 1997). For example, in the present study the system residence time for Crows Pond (in the Bassing Harbor system) is calculated to be *2.6* days, but from the earlier study the system residence time for Crows Pond is *68.6* days. The difference is due to the different system volumes used to compute each numbers, i.e., only the volume of the Bassing Harbor system (102,152,200 ft^3) in this study, and the volume of the entire Pleasant Bay (1,997,780,000 ft^3) for the earlier study. Alternatively, local residence times from these two studies show much closer agreement (1.3 days and 1.8 days, for this study and ACI, 1997 respectively), because these numbers are based on the volume of the same sub-embayment, Crows Pond in this case.

V.5.2 Pre-Breach Conditions

The formation of New Inlet in 1987 altered the hydrodynamics within the Pleasant Bay Estuary. As a result of the inlet, the tide range in Pleasant Bay has increased by approximately 1 ft, with a corresponding improvement to tidal flushing within the northern portions of the estuary. The inlet continues to migrate south and Nauset Beach will return to a morphology similar to the pre-breach form. This pattern of inlet formation and southerly growth of Nauset Beach is cyclical. The two most recent breaches through the Nauset barrier occurred in 1846 east of Allen Point and 1987 east of the Chatham Lighthouse. The anticipated cyclical behavior of the inlet system is based on the work of Geise (1988) who described the historical 1846 breach and the subsequent re-formation of Nauset Beach during the following 140 years. For comparison purposes, the pre-breach 1970's form of Nauset Beach is shown in Figure V-61 and the more efficient 1996 system is shown in Figure V-62.

The modeling effort presented above was performed for the existing (post-breach) conditions based on recently obtained bathymetric and tidal data, as well as information from a previous study of regional hydrodynamics (ACI, 1997). To simulate pre-1987 conditions when the Chatham Harbor/Pleasant Bay system was less hydraulically efficient, a revised model grid was developed as part of this previous modeling effort to simulate the pre-breach estuary (ACI, 1997). As a basis for the model grid, digital data obtained from historic NOAA surveys of the region were utilized to supplement the 1997 bathymetry data. Due to the orientation of the historic inlet, the pre-breach estuary was served by a combination of tides from the Atlantic Ocean and Nantucket Sound. The modeling analysis for the pre-breach estuary utilized Atlantic Ocean tides only (the measured 1997 Atlantic Ocean tide data was used to drive the model); however, an attempt was made to "calibrate" the model to the predicted amplitude damping and phase lags presented in the pre-breach NOAA Tide Tables.

To "calibrate" the pre-breach model, ACI matched the modeled tides to the historic amplitude damping and phase lag presented in the 1986 NOAA Tide Tables. For example, the mean tide range in the Atlantic Ocean offshore of Chatham was predicted to be 6.7 ft, with the tide range reducing to 3.6 ft in Chatham Harbor and 3.2 ft in Pleasant Bay. In general, the modeled pre-breach conditions compared well with the NOAA tide information.

The less efficient pre-breach inlet causes the mean tide range within the system to be reduced by approximately 1 ft (ACI, 1997). The reduction in tide range has a corresponding reduction in flow velocities and volume of water moved through the estuary and its sub-embayments. Pre-breach hydrodynamic characteristics were computed utilizing the models developed for Chatham's Pleasant Bay embayments, and a forcing tide generated from the ACI 1997 pre-breach model scenario. Figure V-63 shows the predicted 1997 Pleasant Bay tide, with the corresponding tide curves for the Bassing Harbor system and Muddy Creek developed as part of this study. A calculation of residence times was performed to evaluate the magnitude of the worst-case pre-breach scenario on tidal flushing. The results of this analysis are shown in Tables V-13 and V-4.

The information presented in Tables V-14 and V-15 indicates between a 10% and 88% increase in residence times for the sub-embayments within the Pleasant Bay Estuary. For most of the estuary, the increase in residence times was between 50% and 70%. There are two primary causes for the substantial increase in residence times for the Pleasant Bay systems: 1) an increase in mean sub-embayment volumes for pre-breach conditions, and 2) reduction in the tide range.

Figure V-61. Topographic map from the 1970's indicating the pre-breach inlet between Morris Island and Nauset Beach.

Figure V-62. Recent nautical chart indicating the location of New Inlet at the breach in Nauset Beach

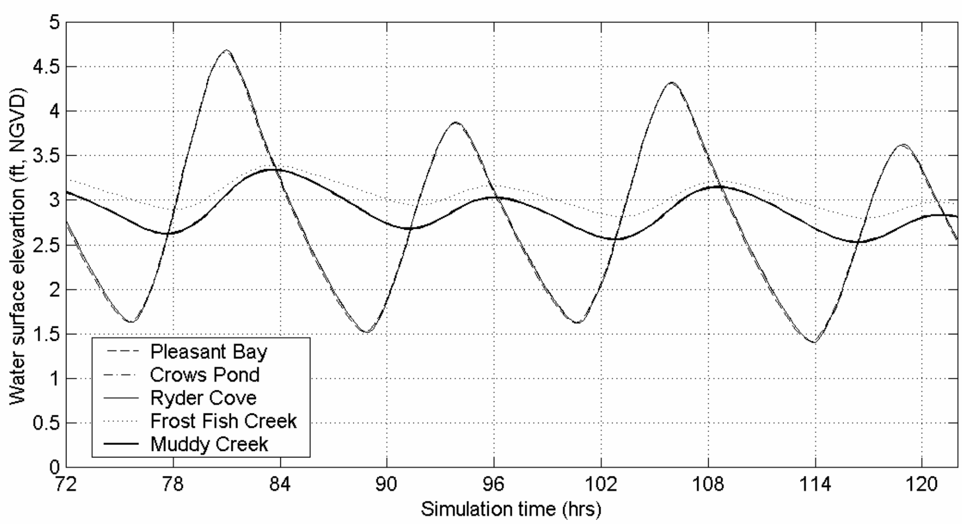

Figure V-63. Plot of two tide cycles of model run results for pre-breach conditions at Muddy creek and Bassing Harbor sub-embayments.

Table V-13. Embayment mean volumes and average tidal prism during simulation period for modeled pre-breach conditions in Pleasant Bay.

System	Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Bassing Harbor	Bassing Harbor (system)	114,689,900	33,724,000
	Crows Pond	58,302,100	13,602,600
	Inner Ryder Cove	22,267,400	8,437,200
	Frost Fish Creek	1,744,700	898,300
	Upper Frost Fish Creek	768,600	119,021
	Ryder Cove / Frost Fish Creek	34,894,300	12,442,600
Muddy Creek	Muddy Creek (system)	6,496,875	870,315

Table V-14. System and Local residence times (flushing rates) for Pleasant Bay sub-embayments for modeled pre-breach conditions.

System	Embayment	System Residence Time (days)	Local Residence Time (days)
Bassing Harbor	Bassing Harbor (system)	1.8	1.8
	Crows Pond	4.4	2.2
	Inner Ryder Cove	7.0	1.4
	Frost Fish Creek	66.1	1.0
	Upper Frost Fish Creek	498.7	3.3
	Ryder Cove / Frost Fish Creek	4.8	1.5
Muddy Creek	Muddy Creek (system)	3.9	3.9

Table V-15. Percent change in residence times from present conditions for Pleasant Bay sub-embayments for modeled pre-breach conditions.

System	Embayment	System Residence Time change (%)	Local Residence Time change (%)
Bassing Harbor	Bassing Harbor (system)	80.0	80.0
	Crows Pond	69.2	69.2
	Inner Ryder Cove	70.7	75.0
	Frost Fish Creek	53.7	66.7
	Upper Frost Fish Creek	18.1	10.0
	Ryder Cove / Frost Fish Creek	71.4	87.5
Muddy Creek	Muddy Creek (system)	30.0	30.0

The sub-embayment mean volumes change due to the increased pre-breach mean tide level (approximately 2.1 ft NGVD for present conditions, and 3.1 ft NGVD for pre-breach conditions, from Table V-16). The reduction in tide range is the greatest of the two factors affecting flushing rates. Table V-16 shows mean-high-water and mean-low-water datums for pre- and post-breach conditions. The post-breach datums were computed using the TDR data collected in August and September 2000 for Ryder Cove. High water levels are similar, but low water levels differ by about 1 ft, therefore the mean tide range of the pre-breach condition is only about 68% of the mean tide range measured in this study. Finally, system and local residence times for each sub-embayment change by different percentages because the change in mean sub-embayment volumes verses mean system volumes is not equivalent. For example, the mean volume of the entire Bassing Harbor System (use for computing system residence times for all sub-embayments in the system) increases by 12% for pre-breach conditions, but the mean volume of Inner Ryder Cove (used to compute local residence time for Inner Ryder Cove) increases by 15%.

Within Muddy Creek, an anticipated increase in residence time of 30% is predicted by the model for the pre-breach conditions. Since the tide range within Pleasant Bay is reduced by approximately 1 ft for pre-breach conditions, the tidal exchange is greatly retarded through the Route 28 culverts. Larger culverts would allow better exchange of tidal waters between Muddy Creek and Pleasant Bay would limit the anticipated increase in residence times as the estuary returns to a pre-breach morphology.

Table V-16. Comparison of tide datums and mean tide levels for pre- and post-breach conditions, for Inner Ryder Cove. Elevations are relative to NGVD 29. Datums for present conditions were computed using TDR data collected in August and September 2000 in Ryder Cove.

Frost Fish Creek	Mean High Water (ft)	Mean Low Water (ft)	Mean Tide Level (ft)
Present conditions	4.2	0.0	2.1
Pre-breach conditions	4.5	1.7	3.1

V.6 ALTERNATIVES TO IMPROVE TIDAL FLUSHING

The two sub-embayments linked to the Pleasant Bay estuary by culverts (Muddy Creek and Frost Fish Creek) exhibit relatively poor tidal flushing. Water quality improvements to these systems likely can be achieved through either resizing of culverts or turning upper portions of the coastal embayments into freshwater ponds. Evaluation of potential alternatives is critical to achieve water quality goals, as well as to avoid adverse environmental impacts.

The hydrodynamic models utilized to evaluate tidal flushing provide the basis for *quantitatively* analyzing the effects of various alternatives on tidal exchange. Using the calibrated models for each system, the model grids were modified to reflect alterations in culvert dimensions and/or bathymetry. Numerical models provided a cost-effective means for evaluating several water quality improvement scenarios. Incorporating hydrodynamic and water quality models was utilized to streamline the alternative selection process.

V.6.1 Muddy Creek

The two culverts running under Route 28 at Muddy Creek each have a height of approximately 2.6 feet and a width of 3.7 feet. Since the surface area of Muddy Creek is relatively large, these culverts are not of sufficient size to allow complete tidal exchange between Pleasant Bay and Muddy Creek. This poor tidal exchange is likely responsible for the water quality concerns for the Muddy Creek system. In addition, replacement of these culverts will likely be an expensive alternative due to the large roadway embankment overlying the flow control structures.

Due to the elevation of Route 28 in this region, the roadway embankment prevents storm surge from overtopping the road and “shocking” the ecosystem in Muddy Creek with a pulse of higher salinity Pleasant Bay water. Therefore, turning Muddy Creek into a completely freshwater system is a viable alternative. Other alternatives considered include turning a portion of the system to freshwater and enlarging the culverts to improve tidal exchange.

V.6.1.1 Alternative M1 – Muddy Creek as a Freshwater System

Gates could be installed on the Pleasant Bay end of the existing culverts to convert the estuarine system to completely freshwater. As mentioned above, the Route 28 embankment would prevent floodwaters from overtopping the road; therefore, the freshwater ecosystem would remain stable during severe conditions. The gates would allow only unidirectional flow from Muddy Creek into Pleasant Bay. Periodic maintenance of the culvert gates would be required, due to their open exposure within Pleasant Bay. A potential environmental drawback to this alternative is the loss of salt marsh that exists within approximately the northern third of the estuary. Since this alternative would eliminate tidal exchange between Muddy Creek and Pleasant Bay, no modeling was performed to evaluate the effect of the gates on local hydrodynamics.

V.6.1.2 Alternative M2 – Muddy Creek as a Partial Freshwater System

To preserve the salt marsh in the lower portion of Muddy Creek and improve tidal flushing characteristics without altering the culvert configuration, a dike could be placed approximately ½ mile upstream from the roadway embankment (see Figure V-64). The region upstream of the dike would be maintained as a freshwater pond, again with a gate that only allowed unidirectional flow from the upper portion of Muddy Creek to the lower estuarine portion. Since the poor tidal exchange through the existing culverts is caused by the small cross-sectional area of the culverts relative to the surface area of Muddy Creek estuary, reducing the estuarine surface area will improve flushing characteristics. For example, hydrodynamic model simulations of dike placement as shown in Figure V-64, reduces the mean-tide estuarine volume by 55%; however, it causes very little reduction in tidal prism. The increase in tide range resulting from Alternative M2 is shown in Figure V-65. In addition, a comparison of tidal flushing improvements is shown in Table V-17.

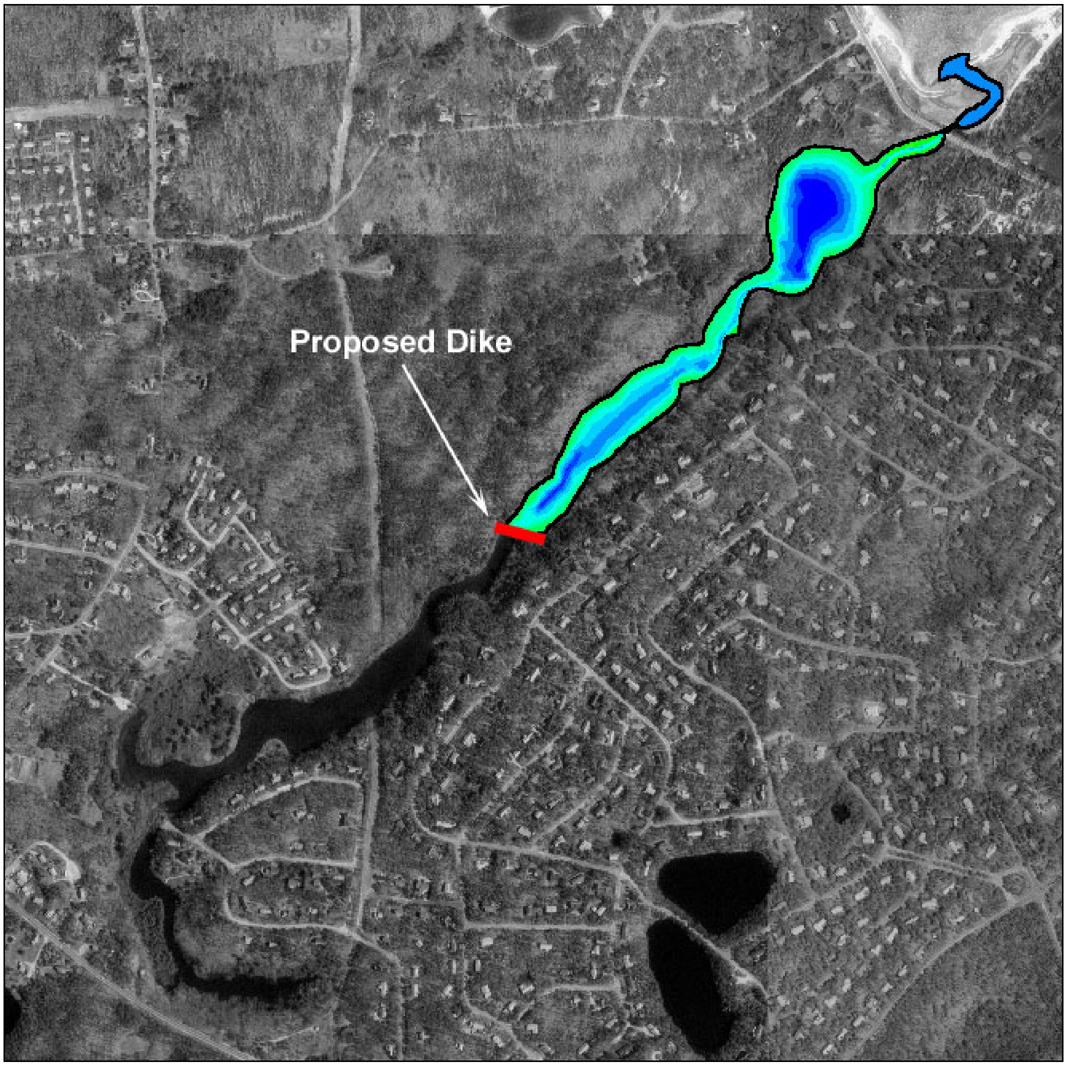

Figure V-64. Muddy Creek Alternative M2 illustrating the approximate position of the dike separating the freshwater and brackish regions.

Design considerations for the dike should include sufficient elevation to minimize potential overtopping during storm conditions. In addition, the freshwater pond level should be set at least 1.0 feet above the anticipated mean tide level in the estuarine section (about 3.5 feet NGVD according to Figure V-64) to ensure flow exits the freshwater section during all phases of the tide. A simple adjustable weir could be designed to fine-tune the water elevation in the freshwater section.

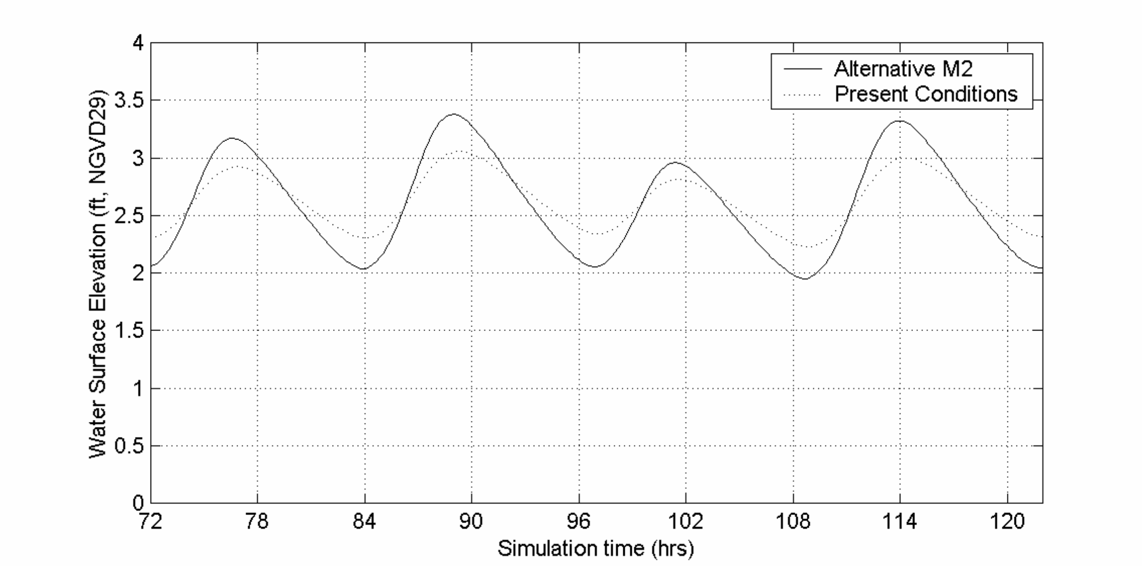

Figure V-65. Modeled tide range for Alternative M2 compared with present conditions.

V.6.1.3 Alternatives M3 and M4 – Increase Size of Route 28 Culverts

Although the Muddy Creek culverts are in good structural shape, it is possible that the Massachusetts Highway Department would consider culvert upgrading as part of the planned Route 28 improvements, if it clearly can be demonstrated that larger culverts are necessary to improve water quality. To assess tidal flushing improvements associated with larger culverts, two alternative culvert sizes were considered: a width of 8 feet and a width of 16 feet. Unlike the existing culverts, the culverts would be designed with a height similar to the tide range in Pleasant Bay (approximately 4.5 feet) to prevent the additional frictional drag associated with totally submerged culverts.

Table V-17 illustrates the change in tidal flushing associated with the two culvert alternatives. The smaller culvert alternative (Alternative M3) provided a similar tide range to Alternative M2. However, the residence time for Alternative M3 is similar to existing conditions, since the tidal prism increases by only about 20% and the mean-tide volume remains similar. Though the larger culvert alternative (Alternative M4) provided a significantly larger tide range, the reduction in residence time was not significantly greater than Alternative M2. The tidal curves for Alternatives M3 and M4 relative to existing conditions are shown in Figure V-66.

Table V-17. Comparison of system volume, tide prism, and residence tides for Muddy Creek for alternatives M2, M3, and M4.

Muddy Creek	system mean volume (ft^3)	tide prism volume (ft^3)	local residence time (days)
Present conditions	5,699,300	982,900	3.0
Alternative M2	3,150,700	957,500	1.7
Alternative M3	5,573,700	1,170,300	2.5
Alternative M4	5,404,600	2,816,100	1.0

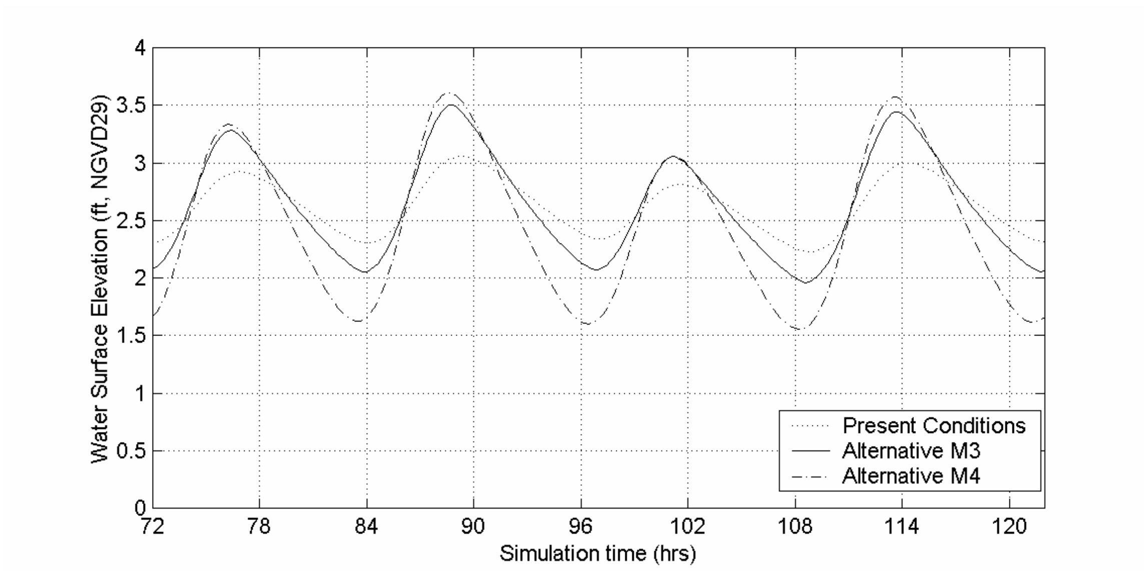

Figure V-66. Modeled tide range for Alternatives M3 and M4 compared with present conditions.

V.6.2 Frost Fish Creek

Two types of flow control structures exist at Frost Fish Creek. First, three partially-blocked 1.5 feet diameter culverts run under Route 28. Approximately 100 feet upstream of these culverts, a single large culvert and a dilapidated weir structure maintain the Creek level well above the mean tide elevation in adjoining Ryder Cove. Since the weir structure likely maintained Frost Fish Creek as a freshwater system, the culverts were adequate for handling the freshwater outflow from the Frost Fish Creek watershed. Following removal of the weir boards, Frost Fish Creek became a salt marsh system with a tide range of less than 0.5 feet. Similar to Muddy Creek, the size of the culverts limits tidal exchange with Ryder Cove and the rest of the Pleasant Bay estuary. The poor tidal exchange is likely responsible for the water quality concerns within Frost Fish Creek.

Since Route 28 in the vicinity of the creek culverts is below the predicted 100-year storm level, occasional overtopping of the roadway is anticipated. If the pond were maintained as a freshwater system, flooding would cause episodic increases in the pond salinity level, with the associated environmental impacts to wetland species. In addition, Frost Fish Creek presently supports a relatively healthy salt marsh system that would be destroyed by converting the system to freshwater. For these reasons, conversion of Frost Fish Creek back to a freshwater pond does not appear to be a feasible alternative. Instead, culvert options were considered to improve tidal exchange and enhance the existing salt marsh.

Since the existing culverts are partially clogged, the Massachusetts Highway Department has indicated a willingness to improve these structures as part of proposed work along Route 28. Two culvert alternatives were evaluated with the hydrodynamic model: Alternative F1 increased the tide range upstream of Route 28 to approximately 1.0 feet by installing a box culvert with a width of 5 ft and a height that allows the top of the culvert to remain above the water surface under most conditions; and Alternative F2 increased the tide range to approximately 1.5 feet by installing a box culvert with a width of 7 ft and a height that again allows the top of the culvert to remain above the water surface. An increase in tide range of greater than 1.5 feet may result in negative impacts to the marsh, because a greater portion of the marsh will be more frequently inundated with salt water; therefore, alternatives with larger culverts were not modeled. However, it may be feasible to reconstruct the weir upstream of Route 28 and utilize this structure to control tidal exchange and water elevations. Adjustment of the weir boards would allow “fine tuning” of the tide range within Frost Fish Creek. In this manner, culverts larger than those presented in Alternatives F1 and F2 below could be installed without impacting the marsh system.

Table V-18 illustrates the change in tidal flushing associated with the two culvert alternatives. The smaller culvert alternative (Alternative F1) provided a tide range of about 1.0 feet, with a significantly reduced local residence time of 1.3 days. The larger culvert alternative (Alternative F2) provided approximately a 1.5 ft tide range, as well as a lower residence time than Alternative F1. The tidal curves for Alternatives F1 and F2 relative to existing conditions are shown in Figure V-67. Due to the substantial tidal attenuation caused by the existing (partially blocked) culverts, the model indicated installation of larger culverts would significantly reduce the mean tide level with a negligible increase in the high tide elevation.

Table V-18. Comparison of system volume, tide prism, and residence tides for Frost Fish Creek for alternatives F1 and F2.

Frost Fish Creek	system mean volume (ft^3)	tide prism volume (ft^3)	local residence time (days)
Present conditions	727,800	125,200	3.0
Alternative F1	618,300	232,800	1.3
Alternative F2	596,000	358,600	0.9

V.6.3 Environmental Effects of Flushing Improvement Strategies

Concerns may arise regarding the potential of increased saltwater intrusion associated with enhancing tidal exchange to Muddy and Frost Fish Creeks. However, tidal embayments with poor tidal flushing characteristics generally have a mean tide level higher than the embayments closer to the ocean. For example, the mean tide level in the Atlantic Ocean offshore of Chatham is between 0.0 and 0.5 feet above NGVD, the mean tide level in Pleasant Bay is approximately 1.7 feet NGVD, and the mean tide level in Muddy Creek is about 2.5 feet NGVD. The hydrology of the estuarine system requires a sloping surface, with the highest long-term mean water level in the upper portions of the estuary and the lowest mean water levels in the ocean. For estuarine systems exhibiting little tidal attenuation, the change in mean water level through the system generally is small. As Figures V-65, V-66and V-67 indicate, the mean tide level is similar or lower than the existing mean tide level for each alternative.

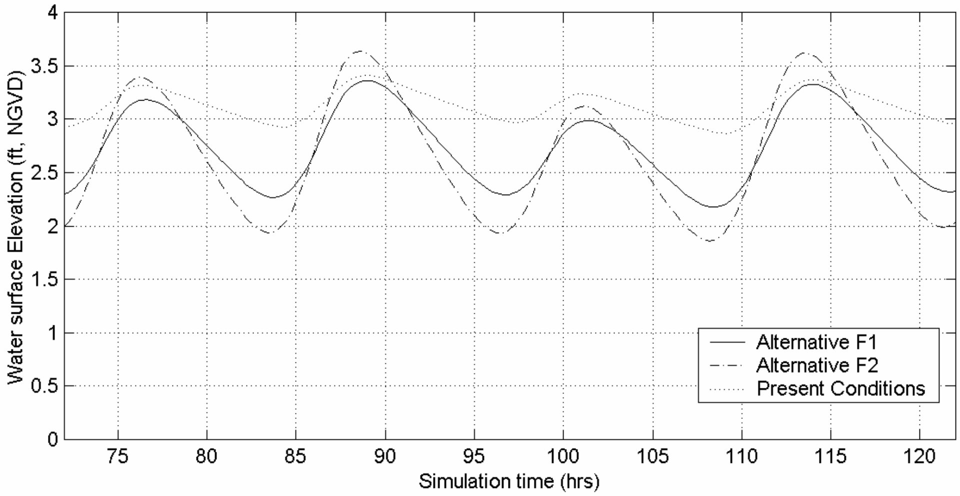

Figure V-67. Modeled tide range for Alternatives F1 and F2 compared with present conditions.

Due to the substantial tidal attenuation caused by the existing Frost Fish Creek culverts, the high tide level for the alternatives also remains similar to the existing high tide level. Only an increase in mean tide level will cause a measurable alteration to saltwater intrusion; therefore, the proposed tidal flushing improvements will have no negative impacts related to increased saltwater intrusion.

Creation of a freshwater system within Muddy Creek will enhance nitrogen attenuation. Since freshwater ponds and/or wetlands are often incorporated into nitrogen "removal" strategies, conversion of a portion of Muddy Creek to a freshwater system will provide two water quality improvement mechanisms: tidal exchange will be enhanced and the freshwater portion will provide natural attenuation of nitrogen. Prior to adopting this alternative for Muddy Creek, an evaluation of impacts to the brackish upper estuary needs to be performed. In addition, the future water quality modeling will analyze the improvements to total nitrogen concentrations that can be anticipated for each alternative.

V.7. SUMMARY

V.7.1 Conclusions

Tidal flushing of estuarine systems within the Stage Harbor System, the South Coast Embayments, and Pleasant Bay Region was evaluated using field measurements (Section V.3) and a calibrated hydrodynamic computer model (Section V.4). Field data included measured tides at eleven (11) locations, detailed depth measurements to augment previous bathymetric survey information, and current measurements taken along cross-channel transects. Field measurements of offshore tides in Pleasant Bay and Nantucket Sound, as well as depth measurements throughout the estuarine systems, provided input data to the computer models. Tide data collected within each sub-embayment were used to confirm the accuracy of the model simulations. For the Bassing Harbor and Stage Harbor systems, current measurements were used to verify the models calibrated with tide data. The computer model simulated water circulation in the estuary, including tides and currents. Two-dimensional current patterns, and water surface elevation were simulated by the model every twelve (12) minutes at thousands of points within each estuarine system. The modeled tides and currents were used to evaluate tidal flushing based on residence times and tidal circulation patterns.

A computer model was developed to simulate accurate tidal hydrodynamics in the Stage Harbor and Pleasant Bay Regions. The accuracy of model simulations was calibrated and verified by comparison to field data. The calibrated model provides a diagnostic tool for future analyses of water quality.

Based on the *local* residence time predictions alone, all of the embayments studied as part of the Stage Harbor system and South Coast Embayments (Stage Harbor, Sulphur Springs, and Taylors Pond) may be considered rapidly flushing systems. The rapid flushing rate of each system typically is an indicator of good relative water quality; however, each system has sub-embayments that exhibit signs of ecological stress, indicative of poor water quality. Therefore, the levels of nutrient loading likely controls water quality within the embayments (especially the upper portions of each system) to a greater degree than the hydrodynamic characteristics of each pond. In addition, it may be more appropriate to utilize *system* residence times to indicate estuarine health in the upper sub-embayments (e.g. Little Mill Pond), since the sub-embayments supplying these upper regions may have relatively poor water quality. For example, Little Mill Pond is flushed by waters traveling through Mill Pond, which exhibits signs of ecological stress.

Based on the *local* residence time predictions alone, much of the Bassing Harbor system may be considered rapidly flushing. Again, the rapid flushing rate of each system typically is an indicator of good relative water quality. The exception to the general rapid flushing of the Bassing Harbor system is Upper Frost Fish Creek (upstream of the Route 28 culverts). Substantial tidal attenuation occurs as a result of the flow restriction caused by under-sized culverts.

Similar to Upper Frost Fish Creek, Muddy Creek also shows substantial tidal attenuation as a result of the flow restriction created by culverts under Route 28. Although the Muddy Creek culverts are significantly larger than the Frost Fish Creek culverts, the greater surface area of the Muddy Creek estuarine system demands a much larger volume of water to raise the water level within the estuary.

The models were used to compute system and local residence times for existing conditions (Table V-12) in each estuarine system. Although tidal amplitude damping was greater across the Bucks Creek and Mill Creek systems than the Stage Harbor system, the limited water depth of these marsh-dominated estuaries (Bucks and Mill Creeks) produced lower overall residence times. Local residence times for the Pleasant Bay Region estuaries were similar to the Stage Harbor Region estuaries, with the exception of Muddy Creek and Frost Fish Creek. Local residence times for Muddy and Frost Fish Creeks (3.0 days for each) indicated reduced flushing for these areas.

Analysis of two-dimensional current patterns revealed that maximum currents within each estuary occurred within the inlets. For example, maximum flood currents were approximately 3.3 and 3.2 feet per second for the Stage Harbor and Bassing Harbor entrances, respectively.

Due to the rapidly changing geomorphology of the Chatham Harbor/Pleasant Bay entrance (New Inlet), a "worst-case" flushing analysis was performed utilizing historic pre-breach morphology and bathymetry. This analysis indicated that residence times would increase between 10 and 88 percent as the system returns to its pre-breach form.

The analysis of alternatives to improve tidal flushing in Frost Fish and Muddy Creeks indicated that a variety of options are available to dramatically improve tidal exchange through the Route 28 culverts. For Muddy Creek, placement of a dike at the approximate mid-point of the system (Figure V-64) would convert the upper half of the system into freshwater. Reduction in the surface area of the tidal portion would reduce the residence time by approximately 50%. Other options for Muddy Creek include increasing the size of the culverts and conversion of the entire estuary to a freshwater system. A modest increase in culvert size at Frost Fish Creek would more than double the tidal exchange. For both Muddy and Frost Fish Creeks, a more complete analysis of environmental impacts associated with improved tidal flushing should be performed prior to implementing project design.